Mortality of Nuclear Weapons Test Participants

Medical Follow-up Agency
Commission on Life Sciences
National Research Council

DOE/EV/01577

STUDIES OF PARTICIPANTS IN NUCLEAR TESTS

FINAL REPORT

1 September 1978 - 31 October 1984

C. Dennis Robinette
Seymour Jablon
Thomas L. Preston

MAY 1985

WORK PERFORMED UNDER CONTRACT
DE-AI08-78EV01577

MEDICAL FOLLOW-UP AGENCY
NATIONAL RESEARCH COUNCIL
2101 CONSTITUTION AVENUE, N.W.
WASHINGTON, D. C. 20418

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The work presented in this report was supported jointly by the Defense Nuclear Agency and the Department of Energy, under Contract No. DE-AI08-78EV01577.

Available from:

Medical Follow-up Agency
National Research Council
2101 Constitution Avenue, N.W.
Washington, D. C. 20418

SUBCOMMITEE ON EXPOSURE AT TESTS OF NUCLEAR WEAPONS

JAMES F. CROW (Chairman), Department of Genetics, University of Wisconsin, Madison, WI

JOHN A. AUXIER, Applied Science Laboratory, Oak Ridge, TN

GEORGE B. HUTCHISON, Department of Epidemiology, Harvard University, Boston, MA

ALFRED G. KNUDSON, JR., The Institute for Cancer Research, Philadelphia, PA

RAYMOND SELTZER, Office of the Dean, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, PA

H. ELDON SUTTON, Department of Zoology and The Genetics Institute, University of Texas, Austin, TX

National Research Council Staff Officers:

C. DENNIS ROBINETTE, Medical Follow-up Agency, Commission on Life Sciences, Washington, D. C.

SEYMOUR JABLON, Medical Follow-up Agency, Commission on Life Sciences, Washington, D. C.

THOMAS L. PRESTON, Medical Follow-up Agency, Commission on Life Sciences, Washington, D. C.

ABBREVIATIONS USED IN THIS REPORT

BIRLS: Beneficiary Identification and Records Locator Subsystem. A Veterans Administration computer file of all veterans who have filed claims for disability or educational benefits, or hospitalization or for whom a death benefit has been claimed.

CDC: Centers for Disease Control, Atlanta, Georgia

DNA: Defense Nuclear Agency

DOD: Department of Defense

ICDA: International Classification of Diseases, Adapted for Use in the United States. Public Health Service Publication No. 1693, U. S. Government Printing Office, Washington, D. C., 1967.

kerma: Kinetic Energy Released in Materials. This measures a radiation field "in free air"

MFUA: Medical Follow-up Agency of the National Research Council

NPRC: National Personnel Records Center. A unit of the National Archives and Records Administration, in St. Louis, MO responsible for storage and servicing of noncurrent personnel and organizational records. Veterans' military service records are stored there.

NTS: Nevada Test Site. The area near Las Vegas where nuclear weapons were tested.

PPG: Pacific Proving Ground. The area surrounding Bikini and Enewetak atolls, in the Pacific, where nuclear and thermonuclear weapons were tested.

rad: Unit of radiation dose; 1 rad = 100 ergs per gram = 0.01 gray. A measure of dose in tissue

rem: Unit of dose equivalent: 1 rem = 1 rad times a Quality Factor (conventionally taken as 1 for X or gamma rays or beta particles, 10 for neutrons, and 20 for alpha particles) = 0.01 sievert.

SMR: Standardized Mortality Ratio

VA: Veterans Administration

VAMI: Veterans Administration Master Index. A microfilm file containing identifying information on approximately 34 million veterans who served during 1917-1971.

ABSTRACT

Stimulated by reports of the excess incidence of leukemia among veterans who had participated at test shot SMOKY at the Nevada Test Site in 1957, a study of mortality, by cause of death, was done on a cohort of 46,186 participants in one or more of five test series. The series studied were UPSHOT-KNOTHOLE (1953) and PLUMBBOB (1957) at the Nevada Test Site, and GREENHOUSE (1951), CASTLE (1954), and REDWING (1956) which were conducted at the Pacific Proving Ground at Enewetak and Bikini.

The participants were traced individually by the use of Veterans Administration records. Death certificates were obtained for deceased veterans from the VA or from the individual state vital statistics records offices. For the participants in each series, the number of deaths attributed to particular causes was compared with the number expected to occur at U. S. cause- and age-specific mortality rates.

A total of 5,113 deaths from all causes was ascertained; this was 11.1 percent of the number of participants. The number was, however, only 83.5 percent of the number expected at U. S. mortality rates. The discrepancy arose from two principal causes: (1) A failure to ascertain about 5 percent of the deaths that actually occurred because they had not been reported to the Veterans Administration or because of failure to match correctly to the VA files; and (2) A real deficiency in the number of deaths from chronic disease, especially cardiovascular disease, in this military population which had been screened for good health at the time of service entry. Mortality from accidents, acts of war, and other

external causes numbered 1,216, and was 6 percent larger than would have been seen had U. S. population rates applied. By contrast, the 1,046 deaths from malignant neoplasms including leukemia were only 84 percent of the number expected at U. S. rates, and the 2,579 deaths from other diseases, only 69 percent of expectation.

Mortality from leukemia among the 3,554 participants at SMOKY - 10 deaths below age 85 - were 2.5 times the expected number (3.97) and the excess, if this had been a single unselected test, would be highly significant ($P < 0.008$).

The comparison of observed and expected deaths from leukemia in SMOKY participants is only one of six that were made. When the leukemia deaths are compared to other deaths in all six data sets, the differences among the series are not significant ($P = 0.16$); thus there is no evidence that the proportion of leukemia deaths in SMOKY was significantly different from those in the other tests. No cancer other than leukemia was ascertained to have occurred in significant excess among SMOKY participants and the number of deaths from other cancers (67) was less than the number expected at population rates (83.8). Both of these results are similar to those reported earlier by the CDC.

A total of 46 deaths from leukemia was ascertained in the entire cohort apart from SMOKY participants. This number is actually less than the 52.4 that would have been expected at population rates. The deficiency is not, however, statistically significant. No significant excess of leukemia was found among the participants at any test series other than PLUMBBOB or among PLUMBBOB participants who were not present at SMOKY. For no other form of cancer was there a consistent excess among the participants at the several test series.

The total body of evidence we have reviewed cannot convincingly either affirm or deny that the higher than statistically expected incidence of leukemia among SMOKY participants (or of prostate cancer among REDWING participants) is the result of radiation exposure incident to the tests. However, when the data from all the tests are considered, there is no consistent or statistically significant evidence for an increase in leukemia or other malignant disease in nuclear test participants.

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INTRODUCTION

In 1979 a preliminary report from the Centers for Disease Control (CDC) indicated that eight cases of leukemia had been identified among 3,224 former servicemen who had participated in a nuclear weapon test, code-named SMOKY, in the PLUMBBOB series at the Nevada Test Site in 1957.[1] This represented an excess of 4.5 cases over the 3.5 expected on the basis of age- and sex-specific population rates; the relative risk of leukemia over a follow-up period of approximately 20 years was 2.3 and was judged by the authors to be statistically significant. The authors concluded that the excess, although formally significant, might be simply the result of chance; if not, the implication was that either low doses of radiation were more carcinogenic than had been supposed or the radiation doses received by the participants were much larger than indicated by the film badge dosimetry that was employed, perhaps because the men inhaled or ingested radionuclides that were not measured by the dosimeters.

Further reports in 1980 and 1983[2,3] extended the observations on the same cohort of veterans to the incidence of all types of cancer and to mortality from cancers and other specified causes over a 22-year period (through 1979). The number of cases of leukemia found increased to 10, including eight deaths, compared with an expected incidence of only 4.0 cases and an expected number

of 3.1 deaths. For the total group of all cancers except leukemia there were deficits of both incidence and deaths, compared with expectation: 102 versus 113.5 for cases and 56 versus 61.2 for mortality. Only for the class of infectious and parasitic diseases was there excess mortality and, in fact, the ratios of observed to expected mortality were usually less than 1; for circulatory diseases the ratio of 0.74 was significantly low.

The 1979 report raised much concern among the general public and, especially, among the hundreds of thousands of men who had participated in tests of nuclear weapons either at the Nevada Test Site (NTS) or at the Pacific Proving Ground (PPG). The possibility that the leukemogenic effects of radiation at low doses had been seriously underestimated would, if confirmed, have important implications for radiation protection standards. The Medical Follow-up Agency (MFUA) of the National Research Council therefore, at the request of the Defense Nuclear Agency (DNA), embarked upon a program aimed at determining whether participants at tests and series other than SMOKY were also at higher than normal risk of death from leukemia or other cancers. Since 1946 the MFUA has maintained a program that uses the medical and administrative records of the Department of Defense (DOD) and the Veterans Administration (VA) in the interests of medical research.

Purpose of the Study and Overview of the Methods Employed

As mentioned above, the CDC study had concerned the participants at shot SMOKY of the PLUMBBOB series. The number of cases of leukemia that were identified among SMOKY participants was compared with the number that might have been expected to occur on

the basis of national age- and sex-specific leukemia incidence rates; the numbers of deaths from cancer and from other causes were similarly compared with the numbers expected on the basis of U. S. cause-specific mortality rates.

The task envisioned for the present effort was, using methodology similar to that employed in the CDC study, to ascertain whether leukemia, other cancer, or any other fatal disease had occurred excessively among participants at atmospheric tests of nuclear weapons other than SMOKY. In particular, it was desired to examine shots other than SMOKY in the PLUMBBOB series and to include participants at other test series, both at the NTS and at the PPG. The CDC study had found similarly increased risks of leukemia among SMOKY participants whether judged by the incidence of or mortality from that disease. The number of SMOKY participants was well under 4,000 (in the end, 3,741 SMOKY participants were identified), while the study contemplated would include many tens of thousands of participants (the total eventually reached nearly 50,000), and individual tracing of each participant was thought to be impractical for both technical and financial reasons. It was decided, therefore, to rely on ascertainment of mortality through the use of existing VA records systems (which are described below). It was appreciated that mortality tracing which relied on the VA's records systems would necessarily be, to some small extent, incomplete; this issue is addressed more completely below. Nevertheless, it was thought that possible deficiencies could be evaluated and compensated for:

- o SMOKY participants would be subjected to the same ascertainment procedures used for participants at other shots and series. If the results for SMOKY turned out to be essentially similar to those reported by the CDC studies, then to that extent the methods would appear to be sufficiently reliable despite the known deficiencies. As described below, the methods passed this test.

- o Since the majority, though not all, of the participants could be characterized as to radiation dose as recorded on film badges or otherwise estimated, evidence of radiation-induced adverse health effects, if they could be identified, should be correlated with the doses. There was no reason to suppose that, if a participant had died, failure to ascertain the fact of death would be more frequent for men with one dose estimate than for men with another.

The plan was to create a number of comparisons of the actual number of deaths ascertained that were ascribed, on the death certificates, to certain causes with the number that would have occurred if U. S. age- and cause-specific mortality rates had applied. The ratio of the observed number to the expected number of deaths in any group, for any cause, is called the standardized mortality ratio, or SMR.

It was recognized that the procedure contemplated has deficiencies:

- o U. S. mortality rates are based on what purports to be a complete accounting of all deaths reported in each year. The "observed" deaths would, however, be subject to attrition from two causes: failure to learn that a veteran had died by the process of matching to VA

records and failure to learn the cause of death because the death certificate was not obtained for a death known to have occurred. For both of these reasons the SMRs calculated will be lower than they should be. As will be explained below, we believe that the SMRs calculated in this study are low by about 10 percent.

- The U. S. mortality rates are based upon the experience of the entire population, which includes those who are sick, as well as those in good health. A military population consists entirely of persons who were in apparent good health at the time of entry into service. It is well known that cohorts of workers in any industry are characterized by lower than average mortality rates because those persons who are too ill to work, and who contribute disproportionately to mortality, are not included. Similarly, military populations are subject to an extreme form of this favorable selection; not only are persons who are actually ill excluded, but also the physical examination excludes from service men who, although not too ill to work, have, for example, blood pressures above accepted norms or urine examinations which show defective kidney function or an early stage of diabetes. This general phenomenon, which in occupational studies is called the "healthy worker effect," is well known in studies of insured populations and has been documented in other studies of veterans.(4)

The problems mentioned above might have been circumvented had the study included explicit controls, that is, a cohort equal in size to the cohorts of test participants but made up of persons of the same age and dates of service who were not present at any test. To create such a control group, however, it would have been

necessary first to characterize the cohort of participants by year of birth, rank, and dates of service to permit the subsequent matching of the control group to the participants on these factors. To obtain the needed information it would have been necessary to consult individual service records, a task which, for tens of thousands of men, would have delayed the study by at least three years. It was thought, moreover, that since estimates of radiation dose would be available for most of the participants a valid assessment of possible health effects attributable to radiation could be made by the comparison of participants whose dose estimates were small, moderate or large.

METHODS AND MATERIALS

Cohorts Studied

The study sample was selected from members of the U. S. armed forces who, by documentation at that time, could be shown to have participated in one or more events of the atmospheric testing program for nuclear weapons.

The operations which constitute the atmospheric testing program are summarized below, with estimated numbers of participants, location, and a statement regarding issuance of film badges. The numbers of participants at the different series sum to 222,000; the total number of men is smaller, however, since some men were at more than one test series. At the beginning of the program it was the practice to issue film badges to a small proportion of participants who were considered to be representative of the whole

group. This practice was changed, to include all participants, after the CASTLE series in 1954.

Announced U. S. Atmospheric Nuclear Tests

Year	Shot/Series	Location	Approximate number of participants	Film badging
1946	Crossroads	PPG*	42,000	Partial
1948	Sandstone	PPG	10,000	Partial
1951	Greenhouse	PPG	7,500	Partial
	Ranger	NTS**	500	Partial
	Buster-Jangle	NTS	6,500	Partial
1952	Tumbler-Snapper	NTS	10,000	Partial
	Ivy	PPG	12,000	Partial
1953	Upshot-Knothole	NTS	21,000	Partial
1954	Castle	PPG	10,000	Partial
1955	Teapot	NTS	8,000	Partial
	Wigwam	PPG	10,000	Total
1956	Redwing	PPG	10,000	Total
1957	Plumbbob	NTS	18,000	Total
1958	Argus	So. Atlantic	4,500	Total
	Hardtack I	PPG	20,000	Total
	Hardtack II	PPG	1,000	Total
1962	Dominic I	So. Pacific	28,000	Total
	Dominic II	NTS	3,000	Total
			222,000	

*Pacific Proving Ground
**Nevada Test Site

A study sample composed of approximately equal numbers of participants in Pacific and continental series was chosen, based primarily on what was believed at the time the study was designed about the quality of available records, for both personnel identification and radiation dosimetry. The UPSHOT-KNOTHOLE (1953)

and PLUMBBOB (1957) series were selected from those conducted at the Nevada Test Site, and GREENHOUSE (1951), CASTLE (1954), and REDWING (1956) from those conducted at Bikini and Enewetak atolls in the Pacific (Table 1).

GREENHOUSE: Ships remained in the lagoon during the detonation and fallout periods and were subjected to considerable fallout.

UPSHOT-KNOTHOLE: Unexpected wind shifts resulted in evacuation of participants at shot BADGER.

CASTLE: Unexpected wind shifts and tripling of the expected yield of shot BRAVO resulted in the greatest number of exposures over 5 rem of any Oceanic series. Some persons (Marshallese, Japanese fishermen and U. S. personnel) were exposed to unexpectedly heavy fallout.

REDWING: This was the first multiple test shot series in the Pacific after the Castle series. Because of the experience at Castle stringent precautions were taken to reduce possible exposures and all participants were issued film badges.(5)

PLUMBBOB: The series of which SMOKY was a part, and the one for which records are best.

Participants were identified by DOD personnel as part of a program begun in 1977 to identify all DOD participants in the atmospheric nuclear tests and determine the extent of the participants' exposure to ionizing radiation. A team from each branch of service was responsible for identifying participants in that branch at each event. Only persons identified from contemporary records sources were entered into the study;

self-reported participants were not accepted. A very small number of women is included among the participants.

Rosters of participants did not exist and each team made use of not only records resources specific to the particular service but also material assembled after a large-scale search of the Federal Archives and Records Centers, facilities of the National Archives and, in some instances, private collections. Deck logs of naval vessels, various unit records such as morning reports, special orders, film badge issue cards and after-action reports were all used. Continued efforts were made to identify all participants, and, as new records sources became available, rosters were updated with new names, additional information on persons already identified, and, in some instances, re-identification of the same persons. The process of identifying participants is a continuing one; an initial list was available in December 1978, but the task had not yet been completed by August 1984. Only 49,148 participants who had been identified by March 1983 were included in the study.

Some men participated at more than one of these series, so that the total of participants in individual series exceeds the number of men actually involved by 1,713 (Table 1). We have no information concerning the number of men who participated also in series other than the five studied here.

Mortality Ascertainment

The follow-up period for mortality ascertainment extended, for all series, to 31 December 1982. The starting date for follow-up for each series was taken to be 1 January of the year following the year in which the series took place, that is,

1 January 1952 for GREENHOUSE participants, 1 January 1954 for UPSHOT-KNOTHOLE, and so forth. For those men who participated in more than one of these series, follow-up was begun on 1 January of the year following the earliest series.

Names, service or Social Security Numbers, and other identifying information on all identified participants were submitted to the VA Beneficiary Identification and Records Locator Subsystem (BIRLS) to learn who had died through 1982 and the location of their VA records. Until 1981 a burial allowance of $250 was paid by VA on behalf of any war veteran not dishonorably discharged who had served for some minimal time (90 days for World War II). The entitlement was changed on 1 October 1981, to provide the burial allowance for only those persons with a service-connected disability or whose incomes were below a statutory level, while retaining the provision of headstones and flags, and adding an allowance for purchase of a cemetery plot. Survivors who file for benefits are required to submit proof of death, usually a certified copy of a death certificate, which becomes part of the veteran's VA record. These certificates, used in determining causes of death, were obtained from local vital statistics offices when they were not available from VA records. Causes of death were coded by nosologists on the staff of the MFUA, according to the Eighth Revision of the International Classification of Diseases, Adapted (ICDA).

On the basis of information returned from BIRLS the files were divided into four groups: (1) matching on name and identifying number - not known by VA to be dead; (2) matching on name and

number - date of death and records location shown on the BIRLS report; (3) no BIRLS record; (4) discrepancies, ranging from minor misspelling of names and single-digit errors in service numbers to different names. Group 1 was not processed further. Death certificates were ordered from the 74 VA Regional Offices and Federal Records Centers for the men known to be dead. Discrepancies were resolved individually by MFUA staff, where possible, and the remainder, with those returned as no record (Group 3), were sent to MFUA staff at the National Personnel Records Center (NPRC) in St. Louis, Missouri, for further processing through various microfilm files there.

The first search at NPRC was in the VA Master Index (VAMI), originally a manual file of some 30,000,000 cards, which now exists on microfilm and contains, in alphabetical sequence, a record for every veteran who had so-called "GI insurance" during World War II and the Korean conflict. It contains also a record for every other veteran on whose behalf a claim was made for death, disability or educational benefits before the VAMI was replaced by BIRLS in 1972; after that time, claims generated an initial BIRLS record if none existed previously. The Master Index was replaced by BIRLS in 1972; veteran mortality prior to that time could be ascertained by reference to VAMI. About 97 percent of World War II veterans, some of whom were recalled to active duty for the Korean conflict, were covered by GI insurance and, on that basis, VAMI cards were created. Although the insurance program was changed during the Korean conflict, coverage was as complete as during World War II. If multiple service numbers had been assigned to a veteran all are

shown on the VAMI card, as well as date of birth, and sometimes Social Security number and information about the death of the man.

Additional identifying information was obtained from VAMI for men identified and used for re-submission to BIRLS if the VAMI card did not show the veteran to have died.

When records were not found in VAMI, further searching was done in other microfilm files, based on branch of service at the time of weapons test participation: The "Army Historical File," the Navy "TRIDEX" file, and the "Marine Corps Stat List." About 10 million persons are included in these files. Name changes, differences in spelling, service number changes, as well as different service numbers were obtained from these files and used for re-submission to BIRLS.

The ascertainment process was iterative, being repeated when new or different material was received from the DOD. Approximately 30,000 records were processed manually through the various microfilm files.

Completeness of Mortality and Cause of Death Ascertainment

If some deaths were missed that occurred in members of the cohorts under study the estimated overall death rate would be diminished in comparison with the U. S. death rate which is used as the standard of comparison. If, as occurred, death certificates (from which causes of death are learned) were not obtained for some deaths, then the SMRs for particular causes of death would be further reduced. The tables for each series show explicitly the number of unobtainable death certificates. A total of 5,113 deaths

were ascertained among the participants in the five series; 272 death certificates, or 5.3 percent, were not obtained. The proportion not obtained ranged from a low of 2.4 percent for SMOKY to 6.6 percent for UPSHOT-KNOTHOLE. Since the numbers obtained and not obtained are shown for each series, adjustments of the SMRs can be made to compensate for the deficiencies in learning about causes of death.

More difficult is the problem posed by failures to ascertain the occurrence of death in the first place. There is some direct evidence concerning this problem.

As previously explained, deaths of veterans which occurred before 1972, and which are known to VA, are shown in the VAMI file, as well as in the BIRLS file. A test of the completeness of mortality ascertainment using the VAMI was made by Beebe and Simon, who reported that, for deaths in 1969 of World War II and Korean conflict veterans, 97 percent of deaths, originally ascertained by methods independent of VA records, were recorded as such in the VAMI. If the few men who had been dishonorably discharged were excluded, the completeness was increased to 98 percent.(6)

A test of the completeness of mortality ascertainment using the BIRLS file has been made by Norman,(7) who reports that 669/703, or 95 percent of a sample of veteran deaths in 1980 were known to the BIRLS file and were retrievable.

These pieces of direct evidence indicate that, by use of the BIRLS and VAMI files, 95 to 97 percent of deaths have been recovered.

In summary, it is estimated that overall SMRs are too low by about 3 to 5 percent because of failure to learn of some deaths

from VA files. Such errors occurred because some deaths were not reported to the VA and because some reported deaths were entered into the computer files with erroneous identifying numbers or because the file was searched with an erroneous identifying number.

Date of Birth Determination

Many participants, particularly those in the Army, did not have a date of birth recorded as part of the identifying information received from DOD. Since test participants were required to have security clearances, arrangements were made with the Federal Bureau of Investigation (FBI) to search their security clearance files, on the basis of name and service number, to provide date of birth for each person found. Approximately 8,500 searches were made, and about 3,500 dates were obtained. For the remainder, records were searched at the NPRC to seek dates of birth. This effort was hampered by the fact that the fire which occurred at NPRC in 1973 had destroyed about 80 percent of the World War II and Korean conflict Army and Air Force records. In the end, dates of birth were lacking for 2,903 men. A small number of men, 59, died between the time of the series and 1 January of the following year (Table 2). Almost all of these deaths were from accidents or other trauma. Some men participated in more than one series, not only among the five included in this study, but others also.

The years of birth for men at the various test series are shown in Table 3.

Radiation Dose Estimation

Exposure to external gamma radiation was measured by film badges. Not all men were issued badges for all events, especially in the early years, and some of the exposures have been estimated from badges issued to other men in the same units or were reconstructed from historical data following procedures established by the Defense Nuclear Agency (DNA).[8] All reconstructions are stated to have been based on "high-sided" or "worst-case" estimates. Film badge exposures were obtained from contemporary documents, film badge issue cards. The cards contained a badge number and space for the man to write his name, service number, and date of issue. The film was later processed and read by densitometer, and the exposure information written on the card, with the current date.

The dosimetry information was supplied by the DNA and, sometimes, by the individual military services. Close examination of the data concerning individual badge readings leads to the conclusion that the readings are not necessarily accurate. Mispunching of dates, service numbers, names and even dose readings occurred. The doses, therefore, must be taken as only approximately accurate. Film badges were not sensitive to neutron radiation, nor could they reflect possible doses from ingested or inhaled radionuclides. The measured total fallout from SMOKY was more than expected and exceeded that from any other shot at PLUMBBOB;[9] we have no information, however, concerning the absolute magnitude of internal radiation doses received by the participants from fallout or neutron-activated materials. Further, since there is no

assurance that all film badge readings were recovered correctly for all participants, the radiation exposure information that has been synthesized from the badge readings supplied for the study must be considered not only to be approximate, but perhaps to err generally on the low side. This low bias is to an unknown extent compensated by the fact that the "reconstructed" dose estimates were purposely "high-sided." In summary, the dosimetry information is inaccurate and may underestimate the true doses.

All of the dose readings supplied for each participant were added together, not distinguishing among tests. For participants at series at the Nevada Test Site, especially, it was not possible to identify unequivocally every participant at a particular shot. The information that was available, however, from the film badges enabled the placement of a participant at the test site during a stated period of time - from the date that the badge was issued until it was read. The date of reading was sometimes immediately after the badge was turned in by the participant, but more often a few days, up to a week, later. By "SMOKY participant," hereafter, is meant a person who was at the Nevada Test Site, who had a film badge issued prior to the date of SMOKY and read after that date, or a person whose name was included on a list of SMOKY participants supplied by DNA or one of the military services.

Distributions of the total dose estimates for each participant, by amount, are shown in Table 4. Table 5 shows the percentage distributions and mean values. The doses reported for the Pacific series (GREENHOUSE, CASTLE, and REDWING) were considerably larger, on average, than those reported for the

UPSHOT-KNOTHOLE and PLUMBBOB series at the Nevada Test Site. It is evident that the original estimate that the doses at REDWING were quite low was erroneous: rather than 96 percent of the doses being less than 3 rem, only 82 percent were below 3 rem and nearly 3 percent above 5 rem. For the entire set of 32,577 men for whom dose estimates were provided to us, 562, or 1.7 percent, exceeded 5 rem, the present annual occupational limit. The doses reported here, however, are sums over all series and therefore were not necessarily received in a single year. On the other hand, possible radiation doses received at series other than the five considered here may, in some instances, have added to the total. It is of interest that the 562 men with doses of 5 rem or more participated in a total of 798 series - for an average of 1.4 series per participant.

The lowest doses were reported for the UPSHOT-KNOTHOLE series - only 10 percent were 100 mrem or more. The doses reported for SMOKY participants were similar to those reported for the entire PLUMBBOB series: rather larger than those reported for UPSHOT-KNOTHOLE, but considerably smaller than those reported for the Pacific tests.

Method of Analysis

The objective of the analysis was to determine 1) whether the excess number of leukemia cases found by the CDC study among participants at SMOKY occurred also among participants at other series and 2) whether other cancers of types that may be induced by exposure to ionizing radiation occurred excessively among participants at SMOKY or other tests.

The method used to answer these questions was, primarily, the calculation of SMRs. The SMR is the ratio of the number of deaths observed, from all causes or any particular cause, to the number that would be expected, that is, the number that would have occurred if standard mortality rates applied.

The U. S. national vital statistics rates were used as standard mortality rates. These are published for each year, and in each calendar year the U. S. rates for that year were used, except that the most recent rates available were for the year 1978, and the rates for that year were used also in the years 1979-1982, inclusive.

The computer program which calculates the expected number of deaths arrays a cohort by five-year age groups in the first year of follow-up and applies to each age group the appropriate annual probability of death for that calendar year (obtained from the death rates). The number of actual deaths in that year is then subtracted from the cohort and each remaining person is aged by one year to obtain the structure of the cohort as it entered the second year of follow-up. This process is continued until the end of the period of observation, 31 December 1982. The procedure effectively adjusts for competing risks the expected number of deaths from each cause.

Unfortunately, the race of each participant was usually unknown, thus making it impossible to use white or nonwhite death rates, as appropriate for each group. Since the age-adjusted death rate for the total U. S. male population was nearly 4 percent larger than the rate for white males in 1976 for total mortality and nearly 3 percent larger for cancer mortality,[10] the rates for white males were used to calculate expected mortality; this was done in an

effort to be conservative, that is to maximize the chance that excess mortality from cancer or other causes would be detected.

Changes in SMRs with Time

The physical examination which is made at the time of entry into the service ensures that few, if any, men who harbor detectable disease will be accepted. Men who have high blood pressure or diabetes or any other disqualifying abnormality are excluded. For cancer there is usually an interval of months to years between the time when the disease is first recognizable and death. It may be expected, therefore, that if an apparently healthy group of men in active service is followed there will be few, if any, early deaths from cancer. Only after enough time has passed to allow the disease to have its onset and then run its course to death will cancer death rates rise to what might be expected to occur in an unselected population. This phenomenon will occur in exaggerated form with respect to those diseases which typically run a very long course - decades - from the time that they can be recognized, perhaps in incipient form, to the time of death. Fatal cardiovascular disease is often the end point of a process that begins with hypertension. Diabetes is usually present for decades prior to the fatal episode. It can be expected, therefore, that the SMRs for these diseases of long course will begin at a very low point for men in active military service and will rise slowly with the passage of decades.

RESULTS

1. PLUMBBOB

1.a. SMOKY

Shot SMOKY of the PLUMBBOB series was fired on 31 August 1957. As noted above, SMOKY participants, for present purposes, include any military personnel who were at the Nevada Test Site on that date and who had a film badge issued on or prior to that date which was read subsequently. Of 3,741 participants, one died before the beginning of the follow-up period for this group (1 January 1958), and for 186 no date of birth could be ascertained. Since there was no assurance that the distribution of dates of birth was the same for those whose dates were not known individually as for those for whom the dates were known, it was deemed more appropriate to calculate expected mortality only for those for whom the date of birth was known. There were 412 deaths among the remaining 3,554 participants (Table 6).

As shown in Table 6, 412 deaths were ascertained among the 3,554 SMOKY participants who were alive on 1 January 1958. For 10 of these deaths the cause is unknown because death certificates could not be obtained. Caldwell et al.[1-3] had reported that in their study there was excessive mortality attributed to causes labeled "Leukemia and Aleukemia," ICD codes 204 to 207. In this study also there were 10 such deaths at attained ages less than 85 while 3.97 would be expected at U. S. national death rates; the ratio of observed to expected - the SMR - was 2.52. The probability that 10 or more deaths would be observed if the expected number is

3.97 is less than 0.008 (Poisson test, one-tail). Other causes of death which occurred in significantly increased numbers were accidents (other than motor vehicle) and acts of war. The non-motor-vehicle accidental deaths were principally from aircraft accidents.

Mortality from disease, on the other hand, was significantly low. This was due, principally, to a very low SMR for arteriosclerotic heart disease: the number of such deaths was only 70 percent of the number that would be expected at U. S. national death rates. This deficiency in deaths from arteriosclerotic heart disease undoubtedly arises from an effect analogous to the "healthy worker effect," that is, that populations of employed persons enjoy favorable mortality experience. In the case of these veterans, the participant had to be in good health, first to pass the physical examination at the time of induction into military service, and second to remain on active duty and so be available to participate in the tests. This phenomenon has been noted previously for cohorts of veterans; see, for example, Seltzer and Jablon.[4]

Deaths from all malignant neoplasms, including leukemia, numbered 77 and were fewer than would have been expected (87.78), but the number was not significantly low ($p = 0.14$, one-tail). There were only 67 deaths attributed to malignant neoplasms other than leukemia, with 83.81 expected, for an SMR of 0.80; the probability that so large a deficit would occur by chance is about 0.03 (one-tail test). Nearly two-thirds of the fatal cancers other than leukemia were of the respiratory and digestive systems; the SMRs for these two forms of cancer were both 0.81.

Details concerning the 11 deaths that were attributed by the death certificates to leukemia are shown in Table 7. Two of the deaths were attributed to chronic lymphatic leukemia (CLL): one at the age of 66 in 1979, dose about 300 mrem, and another at the age of 85 in 1982, with dose stated to be 138 mrem. This last death is not included among those tabulated in Table 6, 8 or 9; the computer program which calculates the expected number of deaths terminates the period of observation at exact age 85 years. CLL, in contrast with other forms of leukemia, has never been found to be associated with previous exposure to ionizing radiation.[11,12] CLL, however, is included in the national leukemia death rates which serve as the basis for calculation of the expected number of deaths. It would, therefore, be inappropriate to remove such cases without, at the same time, correspondingly reducing the "expected" number for the purpose of calculating the significance of the contrast between observed and expected numbers.

Table 8 shows the observed and expected numbers of deaths from some particular cancers during the first and second decade of follow-up and during the final 5-year interval. No noteworthy time trends are seen except for the leukemias, where only one death occurred during the first 10 years after SMOKY. Although radiation-induced leukemias have much shorter latent periods than do radiation-induced solid cancers, according to the BEIR III report,[11] the acute leukemias do have longer latent periods than the chronic forms, and latency is longer following exposure of adults than of children. Since seven of the 10 leukemias were called "acute," the rather long latent periods do not entirely

exclude the possibility that exposure to ionizing radiation may have played a part in their etiology.

Cancer deaths among SMOKY participants are shown in relation to reported radiation dose in Table 9. The deaths from leukemia tend to occur among the participants with larger doses: only 1.34 leukemia deaths would have been expected among participants with doses of 300 mrem or more; actually six occurred. If this were not a selected contrast it could be calculated that the probability of so large an excess occurring by chance is only 0.003. Of the 3,554 SMOKY participants, 1,439, or 40.5 percent, had a dose below 100 mrem or unknown dose; only one of the 10 deaths from leukemia shown in Table 9 occurred in this group of men. There is also a suggestion that respiratory cancer may have occurred preferentially among the participants with the larger doses. However no information about smoking characteristics is available.

1.b. Other PLUMBBOB Shots

Of the 13,685 participants at PLUMBBOB, 3,554 were present at the time of SMOKY. The tests included in operation PLUMBBOB commenced on 28 May 1957 and ended on 7 October of that year. During that period there were 20 atmospheric tests of weapons having yields of one kiloton or more. Besides SMOKY (44 KT) there were such relatively high yield tests as HOOD (74 KT, about 10 weeks before SMOKY), BOLTZMANN (12 KT), PRISCILLA (17 KT), DOPPLER (11 KT, 8 days prior to SMOKY), and WHITNEY (19 KT, 3 weeks after SMOKY).(13)

The ratios of observed to expected mortality are lower for the PLUMBBOB participants who were not at SMOKY than for SMOKY participants (Table 10).

When the files were closed for analysis, death certificates had not yet been received for 75, or 6 percent, of the 1,232 deaths ascertained. The ratios of observed to expected deaths are, therefore, too low, on the average, by 6 percent on this account.

No form of cancer is significantly increased. For cancers as a whole, and for most individual cancers, the observed numbers of deaths are below the expected numbers and in the case of malignant neoplasms of the buccal cavity and pharynx significantly so. Even if the expected number of those cancers is reduced by 10 percent, to 10.94, to compensate for deficiencies in obtaining death certificates and possible under-ascertainment of mortality, the probability that only two such cancer deaths would occur is only about 0.001.

There were only 13 deaths attributed to leukemia and aleukemia, whereas 14.6 would have been expected at U. S. national rates (Table 10). One case of CLL is included among the 13, and two others were unspecified as to type (Appendix A).

Mortality from other diseases, especially cardiovascular disease, is notably low in this cohort. Tables 11 and 12 show the cancer deaths and SMRs in relation to latency (time after exposure) and film badge dosimetry. No trends are noteworthy apart from the tendency of the SMRs to increase with the passage of time in this screened population.

2. UPSHOT-KNOTHOLE

The UPSHOT-KNOTHOLE series of tests at the Nevada Test Site took place between March and June 1953. The follow-up period for participants began on 1 January 1954 and extended, therefore, for 29

years, to 31 December 1982. Included in the tests were 9 atmospheric tests with yields over 10 KT; the largest, Shot CLIMAX, had a yield of 61 KT, larger than the 44 KT of Shot SMOKY in the PLUMBBOB series.

Only a minority of participants wore film badges for every shot in this series. Although more than 2,000 Marines participated at Shot BADGER (23 KT), only two badges were issued per platoon. With respect to Army troops, practice varied: individual participants were issued film badges for shots ANNIE (16 KT) and NANCY (24 KT), but for subsequent shots only one badge was issued for each platoon.[14] Individual dose estimates were then "reconstructed" for persons without film badges, taking into account known activities, weapon characteristics and residual radiation survey data. Although about 11,000 military personnel were believed to have participated in the series, actual film badge doses were available for only about 1,800, the remainder having "reconstructed" dose estimates, if any.[14] It will be recalled that the mean dose for UPSHOT-KNOTHOLE participants was only 291 mrem (Table 5), less than one-third of the average for all participants studied here (934 mrem).

Observed and expected mortality, by cause, is shown in Table 13. Death certificates, from which cause of death was ascertained, were not obtained for 77 deaths, or 6.6 percent of the 1,175 deaths.

Mortality from trauma was larger than expectation, although not significantly increased except for deaths from acts of war. Mortality from disease was significantly low; deaths from all

malignant neoplasms were low, the SMR being only 0.84. Correction for the 6.6 percent of unknown causes of death and a possible 5-percent underascertainment of mortality would raise this SMR to about 0.94.

Deaths from leukemia - 13 - were nearly equal to the expected number of 13.2. Details are shown in Appendix A. Mortality from diseases of the cardiovascular system was very low, as is usual in these cohorts. No cause was noteworthy for an excessive number of deaths. Tables 14 and 15 show the variation in mortality from certain forms of cancer in relation to follow-up interval and reported radiation dose.

3. GREENHOUSE

Operation GREENHOUSE took place in April and May 1951, at Enewetak, and included four tower shots, one of which, EASY, had a yield of 47 KT. Yields for the other three have not been announced. Although 7,322 military personnel, representing all services, were reported to have participated (in some sense), only 3,093 have been identified for this study. The Defense Nuclear Agency report on this operation[15] states:

> Film badges were issued to individuals who possibly could have been exposed to radiation while performing their duties; such as those visiting any of the islands made radioactive by the shots, boat pool crews, radiation monitors, aircrews, aircraft decontamination personnel, and runway crash crews. In addition, over 75 film badges for each test were distributed among the six participating ships, to be worn from the day of the test and 7 days thereafter. Of the approximately 9,350 men in the test area during all or part of the testing operations, 2,416 were badged one or more times. Film badges for personnel

entering radioactive areas normally were issued and turned in daily. Boat pool, air crew, and ship badges generally were issued for a week.

Dose estimates were available for this study for 2,099 persons (Table 4) of the 2,416 stated to have been badged one or more times.

Follow-up was begun as of 1 January 1952 and extended for 31 years to 31 December 1982. There were 410 deaths among the 2,947 participants, or 13.9 percent.

The SMRs are shown in Table 16. Deaths from trauma exceeded expectation; in part this resulted from a large number of war deaths, but mortality from motor vehicle accidents was also high.

Mortality from disease was below expectation, especially for arteriosclerotic heart disease, the most common cause of death. Cancer mortality was also low both in total and for every specific malignant neoplasm that was tabulated. In particular, only a single death from leukemia (acute myeloid - Appendix A) was reported, while 4.43 would have occurred at U. S. leukemia death rates for whites. The discrepancy is not statistically significant.

Cancer mortality was lower than expectation, the SMR being only 0.74. The deficiency is presumably a manifestation of the "healthy worker" effect, and clearly wore off as time passed. By the 1972-1982 period, 20 to 31 years after GREENHOUSE, the SMR for all cancer mortality had increased to 0.92 (Table 17).

Cancer mortality appeared to be quite unrelated to the reported gamma radiation doses (Table 18). The single death from leukemia was in a man whose dose is not known.

4. CASTLE

The CASTLE series was held in April and May 1954 at Bikini and Enewetak atolls and included six thermonuclear devices which had yields in the megaton range, the highest yield being the BRAVO shot of 15 megatons (MT), the greatest yield of any United States weapon exploded in the atmosphere.(16) The BRAVO test significantly exceeded its expected yield and released large quantities of radioactive materials into the atmosphere. The consequence was that some persons stationed on atolls or who were aboard vessels were exposed unexpectedly to contamination by radioactive materials, which resulted in acute radiation effects, including beta burns. A few members of the task force had film badge readings reported to be in the range of 78 to 95 R.(16) Twenty-three Japanese fishermen aboard the ship Lucky Dragon were exposed to heavy fallout some 3 hours after the detonation. The crew members reported symptoms of acute radiation injury, and one later died. It is not clear whether the death was directly a result of the radiation exposure. Also exposed to relatively large doses were 25 U. S. servicemen on Rongerik atoll and 239 Marshallese, 82 on Rongelap and Ailinginae and 157 on Utirik.

There were 11,309 CASTLE participants identified for this study; dose information, however, was supplied for only 7,595.

The Defense Nuclear Agency report on CASTLE shows data for 8,735 exposures to badged military personnel, including 1,212 more than 3 R.(16) Available for this study, however, is dosimetry for only 7,595 military participants (Table 4), with 1,032 over 3 rad.

The overall SMR for CASTLE participants was 0.90; 1,129 deaths were ascertained, whereas 1,249.33 would have occurred at population rates (Table 19). Death certificates were not obtained for about 5 percent of the ascertained deaths; since the mortality ascertainment through the VA files may be low by 5 percent, the overall SMR would be estimated to be about 0.95, and the SMRs shown in Table 19 for individual causes of death may be, on the average, too low by about 10 percent.

In general, the SMRs for traumatic deaths are high, especially for accidents (1.19) and acts of war (2.14). The SMRs for deaths from disease are low, especially for cardiovascular disease (0.78). The SMR for mortality from all malignant neoplasms is 0.91 and correction for underascertainment would bring the ratio very close to 1.00. The SMR for leukemia and aleukemia slightly exceeds 1, but the contrast between 14 such deaths that occurred and 12.22 expected is not statistically significant. Even if the expected number is reduced by 10 percent to 11.0, to correspond to the estimated 10 percent deficit in the observed number, the probability of an excess of 3 cases (14 observed vs. 11 expected) arising by chance is 0.22 and is far from significant. The 14 deaths from leukemia include two cases of CLL and two which were unspecified as to type (Appendix A).

Table 20 shows the time trends for cancer mortality. By the years 1975-1982, that is, 21 to 28 years after CASTLE, the SMR for mortality from all malignant neoplasms was 1.01; digestive cancer deaths were a little low (SMR 0.77), but all other forms of cancer shown in the table were a little high. None of the SMRs exceeds 1.00 significantly, even in this late time period.

The 220 observed cancer deaths and corresponding expected numbers are shown for certain types of cancer by the reported radiation dose in Table 21. Neither for all cancers nor for any particular site, including leukemia, does there appear to be any tendency for the deaths to cluster among the men with the larger reported doses. Indeed, the leukemia deaths are characterized by low reported doses: for men with less than 300 mrem there were five leukemia deaths compared with 1.82 expected.

5. REDWING

The REDWING series of 17 tests of thermonuclear devices took place at Bikini and Enewetak atolls in May, June and July 1956. Only a few of the device yields have been announced, but those range from 13.7 KT to 5 MT. It was the first test series in the Pacific test area for which individual dosimeters were to be provided to all participating personnel.(5) However, some personnel on ships that operated only occasionally in the area during the testing period were apparently not badged.

The overall SMR for REDWING participants was 0.88 (Table 22). The SMR for traumatic deaths was 0.99. An allowance for a 10-percent deficit in counts should be made for particular causes of death because of losses of about 5 percent from incomplete ascertainment of deaths in VA files and nearly 5 percent of the ascertained deaths for which death certificates, and hence causes of death, were unavailable.

The SMRs for death from disease were low, notably so for cardiovascular disease. Mortality from malignant neoplasms almost equaled expectation, or even exceeded it slightly, taking account of

the deficiencies in ascertainment mentioned above. The only cancer for which mortality was significantly high was genital cancer. The excess was actually due to an excess number of deaths from cancer of the prostate. Since prostate cancer has never been demonstrated to be one especially susceptible to induction by radiation,[11,12] the excess may well be explainable in terms of the very large number of comparisons that have been made; it must be expected that, by mere chance, 5 percent of comparisons in which no real differences exist should return a "significant" result. If, as here, eight independent comparisons are made (for eight types of cancer in Table 22) the chance that at least one comparison will, by chance, return a "significance test" value of 0.05 or less is 34 percent.

Only eight deaths from leukemia were found, compared with 10.46 expected. Seven were called "acute leukemia," and one was not specified (Appendix A). This last, unspecified, case was in a man who was also present at UPSHOT-KNOTHOLE and is included in the tables for that series, in addition to those for REDWING.

The observed and expected cancer deaths are distributed by time in Table 23. There are no remarkable time trends either for all cancers or for any of the four diagnostic groups tabulated. Similarly the data are arrayed according to the reported radiation dose in Table 24. There is no tendency towards increasing SMRs with increasing dose either for all cancers or for any of the four components that are tabulated.

6. Combined Series

There were 46,186 military participants at one or more of the five test series studied here for whom dates of birth were available and who survived at least to 1 January following the

series in which they participated. The observed and expected mortality, by cause, is shown in Table 25.

The overall SMR was 0.83. As noted earlier, it is estimated that about 5 percent of the deaths that actually occurred were not ascertained through the use of VA files. Correction for this loss would raise the overall SMR to about 0.88. Although 5,113 deaths were ascertained, only 4,841 death certificates were received. The 272 missing certificates represented 5.3 percent of the deaths, and the observed number of deaths ascribed to particular causes is estimated to be underestimated by about 10 percent in total, from both underascertainment of deaths and the unavailability of death certificates.

The SMR for death from external causes was 1.06; correction for undercounts might bring this to about 1.16. It is evident that the SMR for motor vehicle accidents, shown as 0.91, would, after correction, be about 1.01, so that the actual experience was close to expectation. The high SMR for external causes of 1.16 (adjusted for underascertainment) derives principally from two sources: acts of war, which accounted for 77 deaths vs. only 19.07 expected, and "other" accidents, where there were 457 deaths, compared with 370.15 expected. This last category included 121 deaths from accidents involving aircraft.

The SMR for death from all diseases was low, only 0.73, or an adjusted 0.80. The principal contributor to the deficit is cardiovascular disease, for which the SMR is only 0.68. The deficiency in deaths from cardiovascular disease results from the "healthy worker" effect.

Table 26 shows that the SMRs for death from all diseases increased regularly from 0.52 in the first 10 years of follow-up to 0.84 beyond 20 years, as the effect of screening wore off. The time trends in the SMRs for different causes of death varied considerably, however. There were increases with time in the SMRs for all malignant neoplasms and for most particular kinds of cancer, especially cancers of the digestive and respiratory systems, leukemia and aleukemia and other cancers of the lymphatic system. For cancers of the genital system the SMRs were low for the first 10 years, then increased with increasing duration of follow-up; this coincides with the transition from testicular cancers principally in the earlier years to cancer of the prostate in the later years. The 58 genital cancers included 45 cancers of the prostate (Appendix B). Why prostate cancer should be elevated in these men (as it is, significantly) is not clear; that cancer has not been associated in the literature with exposure to ionizing radiation. Moreover, there is no association between the SMRs for genital cancer and the reported radiation doses (Table 27).

The SMRs for cardiovascular disease in the five combined series were initially very low, as might be expected in a military population, then increased regularly with the passage of time (Table 26). Beyond 20 years the SMR was only 0.75, and even allowance for a 10-percent deficit in notifications would not bring the value up to unity.

Death from cirrhosis of the liver was relatively uncommon during the first 10 years (SMR of 0.50) but increased with the passage of time and, during the last time period, reached a value of 1.12.

The mortality experience for the entire roster is shown in relation to the reported total radiation dose in Table 27. No tendency for an increase in SMRs with increasing dose is seen for all diseases or for any of the specific diseases tabulated. In particular, the SMRs for death from malignant neoplasms show no association with dose level and are below unity for the total series and for most of the individual dose categories. In particular, there is no trend towards increased leukemia mortality with increasing dose, although, because of the relatively small numbers of cases in the individual dose categories, the SMRs are quite variable. It remains true, however, that the overall SMR for leukemia of 0.99 is the second largest for any form of cancer, exceeded only by that for malignant neoplasms of the genital system, 1.11. The relatively large SMR for leukemia results from the inclusion of SMOKY; for the entire experience excluding SMOKY the observed and expected numbers of leukemia deaths are 46 and 52.40, and the SMR is 0.88.

Although multiple myeloma has been identified as a malignancy that can be induced by ionizing radiation, there was no evidence that this disease has occurred excessively among the men studied here: there were only 16 deaths attributed to multiple myeloma in the total series, while about 21 would be expected in a cohort of this size and age composition.

DISCUSSION

This investigation confirmed the reports by Caldwell et al.[1-3] that an excessive number of leukemia cases has occurred among participants at the SMOKY test of the PLUMBBOB series in 1957. No evidence, however, was found that any other form of cancer had occurred excessively among 3,554 SMOKY participants that we studied; no evidence of excess leukemia or any other form of cancer was found among the 10,131 participants at PLUMBBOB who were not at SMOKY; and no evidence was found that there was excessive mortality from any form of cancer among the participants at UPSHOT-KNOTHOLE, GREENHOUSE, CASTLE or REDWING, except for increased genital cancer, which was significant among REDWING participants. The particular SMOKY subgroup of 3,554 men, out of a total of 46,186, is the only one that showed excessive mortality from a form of cancer known to be induced by ionizing radiation.

Caldwell et al.[3] suggested that the "positive findings [concerning SMOKY] may be either attributable to chance or the result of an unknown combination of factors." It may, of course, be that the leukemia excess associated with SMOKY was a chance aberration; it seems important, however, to consider all of the possibilities.

Is the finding a chance observation? The contrast of 10 leukemia deaths (under age 85) that we have identified versus an expected number of 3.97 is associated with a significance test probability of only 0.008; that is, there are only eight chances in a thousand that, if the true expectation is 3.97, 10 or more will

occur. Rothman has pointed out, however, that attention was drawn to the SMOKY cohort by the occurrence of leukemia in a veteran who had been at SMOKY and that under these circumstances it is necessary to adjust the probability calculation to exclude the index case.[17] If this is done, the very low value of 0.008 is increased to 0.02; this is still a small probability, but one which is less difficult to reconcile with the hypothesis that ordinary random variation might have been responsible for the finding.

There were many test firings at which thousands of military personnel were present and each presented an opportunity for a leukemia excess to occur by chance; in fact, for six data sets, the chance is about one in nine that at least one will be marked by an "excess" of leukemia which is characterized by a "significance test" value of 0.02 or less. For the six data sets analyzed here, the proportions of deaths ascribed to leukemia are not significantly heterogeneous: the probability that the ratios would vary as much as they do is 0.081 or, if the index case is removed, following standard practice, the probability is 0.16.

If the excess occurrence of leukemia was in fact a consequence of radiation exposure among SMOKY participants, the question arises as to how the experience is reconcilable with the general body of information concerning radiation leukemogenesis.

There were 11 deaths from leukemia: 10 which are included in Tables 6, 8 and 9, and one which was not included because it occurred at age 85. Two of the 11 were diagnosed as chronic lymphatic leukemia: one death in 1979 at the age of 67, that of a field grade officer who had been attached to the Visitor's Bureau;

and another in 1982, at age 85, that of a former sergeant, who had been a member of the Camp Quartermaster group. Since CLL is considered to be a disease which is not induced by ionizing radiation,[11,12] interest centers on the remaining nine cases.

By applying, on an age-specific basis, the ratios of non-CLL to total leukemia mortality, it was determined that the expected number of leukemia deaths (3.97) could be apportioned as 0.88 from CLL and 3.09 as non-CLL. The probability that nine or more non-CLL cases would be observed is 0.005; the probability that eight or more would occur is 0.014.

Three of the cases occurred in former members of an organization called Task Force Warrior, a provisional unit which included Company C, 1st Battle Group, 12th Infantry Regiment. The film badge radiation doses for these three men were 105, 430 and 615 mrem. Task Force Warrior also included 40 members of a Canadian Army platoon. The analysis of radiation exposures to the members of Task Force Warrior, prepared for DNA,[18] states that the total strength of the Task Force consisted of 563 U. S. troops plus the 40 Canadians, who are not included in the present study. No unit which participated at SMOKY except Task Force Warrior contributed more than a single leukemia case.

A careful analysis of the movements of the Task Force members both prior to SMOKY and during the SMOKY exercise itself led the authors of the report on Task Force Warrior[18] to the conclusion that the mean free-in-air exposure of these men was 970 ± 270 mrem (90 percent confidence limits). This contrasts with a mean film badge reading of 575 ± 250 mrem. The discrepancy results from

the fact that the badges were not sensitive to neutrons; although the Task Force was stationed so far from the SMOKY ground zero (about 7.5 miles) that no measurable prompt radiation would have been received from the detonation itself, subsequent maneuvers towards the point of detonation resulted in receipt of gamma doses from neutron-induced activity. Further, the Task Force had witnessed Shot DOPPLER (11 KT, 23 August) from trenches at distances between 2,800 and 2,900 meters from ground zero and received radiation doses from both neutrons and gamma rays. Moreover, rehearsals of operational plans for SMOKY were carried out in some areas which were contaminated by local fallout from previous tests. The report summarizes the estimated free-in-air doses as:(18)

From Residual and Induced Radiation (mrem)	490
DIABLO field	290
SHASTA field	130
Others	70
From Prompt Radiation (mrem)	
DOPPLER	239 to 845
Total	729 to 1,335

That the "best estimate" of mean free-in-air dose to the members of Task Force Warrior (970 mrem) is 1.69 times the mean film badge dose that they quote (575 mrem) does not necessarily mean that all film badge doses underestimated actual doses in the same ratio; the discrepancy arises chiefly from two sources: the badges did not register the neutron doses from Shot DOPPLER; and the troops were bent over in trenches on the occasion of DOPPLER, thus interposing their entire upper bodies between the incoming radiation and the

film badges, worn on the front of the body. These considerations would apply only to other troops who occupied trenches near enough to ground zero of any shot for significant prompt radiation to be received. The principal mode of exposure to most participants, however, was fallout or residual radiation; there is no special reason to suppose that film badge dosimetry would be seriously in error for gamma rays from these sources of exposure.

A second task force, named Big Bang, consisted of 167 officers and men. This group observed SMOKY from a point 17 miles from ground zero (News Nob), so no prompt radiation from SMOKY was received. On 2 September, however, 110 of these men witnessed Shot GALILEO (11 KT) from a distance of 4,500 meters (2.8 miles).[18] Prompt radiation accounted for doses less than 10 mrem. Immediately after GALILEO, however, the group undertook exercises, including an infiltration course on ground where there was still considerable residual radiation from SMOKY, fired just two days earlier. Most of the radiation exposure to these troops resulted from these activities. The range of film badge measured doses for the 110 men was 860 to 2,980 mrem, and the average was 1,900 mrem.[18] One death from acute myelogenous leukemia occurred among members of the task force; this man had an accumulated film badge dose of 1,250 mrem.

If it be supposed that the observed excess of leukemia cases among SMOKY participants was a consequence of the radiation received, what implications does that have? The Committee on the Biological Effects of Ionizing Radiations (BEIR) of the National Reseach Council in its 1980 report[11] estimated the excess

incidence of leukemia and bone cancer for the period up to 30 years after irradiation as 2.596 cases per million persons per year per rad to the bone marrow, for males aged 20-34 at the time of irradiation. The rate for bone cancer is said to be 0.05; subtracting that amount from the total, 2.546 is obtained as the rate for leukemia (excluding CLL) alone. That estimate was based on a so-called "linear interpolation," that is, the assumption that the excess leukemia rate is strictly proportional to the radiation dose, with no allowance for lower effects from low doses or dose rates. Alternative interpolation formulas which take account of dose rate and low dose effects would yield smaller values for the induction rate at the levels of exposure that are of concern here.

The BEIR risk estimates are in terms of dose to the bone marrow, whereas film badges measure, essentially, kerma free in air. Kerr et al.[19] have estimated that for the gamma ray component of prompt weapon radiation the ratio of the mean marrow dose to kerma varies from 0.77 to 0.87, depending upon distance from ground zero and orientation with regard to direction to that point.

The 3,554 SMOKY participants generated 77,660 person-years of observation through 31 December 1982, an average of just under 22 years. Applying the rate cited by BEIR for excess leukemias of 2.546 cases per million person-years per rad, the number of excess leukemias is predicted to be 0.2 cases. The total number of leukemias expected among SMOKY participants would be, then, 4.17: 3.97 at population rates plus 0.2 radiation-induced excess cases. This calculation employs a hypothetical mean marrow dose of 1 rad, which seems maximal; the mean film badge dose was 571 mrem

(Table 5); the ratio of actual dose to film badge dose for Task Force Warrior was estimated to be 1.69. Although this ratio would apply only to radiation dose received by men in trenches sufficiently close to ground zero to receive prompt radiation, if it is applied to the entire SMOKY cohort, a hypothetical dose of 965 mrem is calculated. This should be reduced because attenuation of the radiation by overlying tissues results in a dose to the bone marrow of about 80 percent of the surface dose;[19] but if this is ignored, an upper limit for the mean marrow dose of about 1 rem is obtained.

Would this be enough to explain the excess? The chance that 10 or more cases would be observed if the expectation were 4.17 is 0.0106; the chance that nine or more would be seen is 0.0269.

SMOKY Leukemias

Kind of leukemia	Expected number	Basis	Probability of observing	
Total	3.97	Population rate	10+	0.0077
			9+	0.0205
	4.17	Population rate plus 0.2 induced by 1 rad marrow dose	10+	0.0106
			9+	0.0269
Total minus CLL	3.09	Population rate	9+	0.0046
			8+	0.0140
	3.29	Population rate plus 0.2 induced by 1 rad marrow dose	9+	0.0068
			8+	0.0195

If it is hypothesized that the leukemia risk estimate provided by BEIR is too low by a factor of two, so that the excess annual rate is really about 5.1 cases per million persons per rad, then the expected number of excess cases would be 0.4, instead of 0.2; the same result would follow if it is assumed that the mean marrow doses were 2 rem, not 1. In this case, the probability of observing eight deaths from leukemia (excluding CLL) with an expected number of 3.49 (3.09 population rate plus 0.4 excess) would be 0.026, still a small value, but not so small as to make totally implausible the hypothesized risk and dose estimates.

In summary:

- If the excess of leukemia cases among SMOKY participants resulted from gross error in generally accepted risk estimates for radiation-induced leukemia, then excesses should have been seen among the participants at other shots and series, but they were not.

- The excess of leukemia among SMOKY participants could have been a chance finding, despite the low "significance test" result. Since independent comparisons of leukemia mortality could be made for many different groups of test participants, it would not be unexpected that one comparison, merely by chance, should yield a "significant" result.

- The excess might conceivably have resulted if the radiation doses to SMOKY participants were much larger than has been estimated. We have no information concerning this possibility; the question was not within the scope of the study.

CONCLUSIONS

1. The finding by Caldwell et al. that an excessive number of cases of leukemia has occurred among former participants at Shot SMOKY of the PLUMBBOB series was confirmed.
2. No evidence was found that leukemia mortality was increased among participants at PLUMBBOB tests other than SMOKY or among participants at UPSHOT-KNOTHOLE, GREENHOUSE, CASTLE or REDWING.
3. Generally accepted estimates of the rate of excess leukemia induction per rem when applied to estimates made by DNA of the radiation doses to participants result in an expected increase of leukemias among SMOKY participants of less than 0.2 case. The observed excess mortality from leukemia among these men then, either was a chance aberration or argues that the mean radiation doses at SMOKY (but not at the other test series) were several times the doses recorded by the film badges that were used.
4. No evidence was found that any cancer other than leukemia occurred excessively among former SMOKY participants.
5. Mortality from cancer in all groups of participants was, in general, found to be less than the number expected at population death rates and mortality from other disease was much less than expected, a consequence of selection for good health by the physical screening employed for active duty servicemen.
6. Although there were significant excesses of leukemia among SMOKY participants and of prostate cancer among REDWING participants, no form of cancer was found to be increased in more than one

test series. Since many independent comparisons of cancer rates were made, the two "significant" excesses may well have resulted from chance.

7. The total body of evidence we have reviewed cannot convincingly either affirm or deny that the higher than statistically expected incidence of leukemia among SMOKY participants (or of prostate cancer among REDWING participants) is the result of radiation exposure incident to the tests. However, when the data from all the tests are considered, there is no consistent or statistically significant evidence for an increase in leukemia or other malignant disease in nuclear test participants.

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Table 1

Test Series Included in this Study, Dates, and Numbers of Participants

Series	Date	Location	Number of shots	Number of participants
GREENHOUSE	1951	Pacific	4	3,093
UPSHOT-KNOTHOLE	1953	Nevada	11	10,365
CASTLE	1954	Pacific	6	11,674
REDWING	1956	Pacific	17	10,564
PLUMBBOB	1957	Nevada	30	15,165
TOTAL				49,148*

*The total is less than the sum because there were 1,713 multiple test participants.

Table 2

Participants Included and Excluded from Mortality Comparisons, by Cause of Exclusion

Series	Number of participants	Birth date unknown	Died before follow-up period	Retained for mortality comparisons*
GREENHOUSE	3,093	141	5	2,947
UPSHOT-KNOTHOLE	10,365	661	10	9,694
CASTLE	11,674	348	17	11,309
REDWING	10,564	348	14	10,202
PLUMBBOB	15,165	1,467	13	13,685
SMOKY**	(3,741)	(186)	(1)	(3,554)
TOTAL***	49,148	2,903	59	46,186

*Expected mortality can be calculated only for those of known date of birth.

**Included in PLUMBBOB.

***Totals are less than the sum of the five series because there were 1,713 multiple test participants; 1,651 of these were retained for mortality comparisons.

Table 3

Year of Birth by Series, Eligible Participants

Year of birth	Total	GREENHOUSE	UPSHOT-KNOTHOLE	CASTLE	REDWING	PLUMBBOB	
						Total	SMOKY**
≤1899	80	4	29	7	9	31	2
1900-1904	237	18	76	17	18	108	23
1905-1909	767	46	153	69	71	428	73
1910-1914	1,783	126	389	210	210	848	132
1915-1919	4,171	324	879	544	705	1,719	298
1920-1924	5,654	605	1,041	1,006	1,069	1,933	352
1925-1929	8,192	1,014	2,443	1,730	1,229	1,776	440
1930-1934	19,136	810	4,568	7,213	3,333	3,212	1,147
1935-1939	7,784	0	116	513	3,557	3,598	1,078
≥1940	42	0	0	0	1	32	9
TOTAL	47,837*	2,947	9,694	11,309	10,202	13,685	3,554

*Includes 1,651 men present at more than one series who are counted in each.
**The numbers of SMOKY participants are included in the PLUMBBOB Total column.

Table 4

Gamma Radiation Doses by Series,
Number of Participants

Series	Total	Dose unknown	Gamma dose in millirem*						
			Total dose known	Less than 100	100–299	300–999	1,000–2,999	3,000–4,999	5,000+
GREENHOUSE	2,947	848	2,099	260	124	541	1,002	110	62
UPSHOT-KNOTHOLE	9,694	3,953	5,741	5,147	71	113	184	157	69
CASTLE	11,309	3,714	7,595	662	954	2,543	2,404	752	280
REDWING	10,202	997	9,205	1,075	837	2,970	2,700	1,365	258
PLUMBBOB	13,685	4,208	9,477	4,064	2,015	2,131	910	228	129
SMOKY**	(3,554)	(114)	(3,440)	(1,325)	(780)	(849)	(391)	(56)	(39)
TOTAL***	46,186	13,609	32,577	11,057	3,908	8,061	6,695	2,294	562

*The gamma doses for each participant have been summed over shots and series studied here. Some men participated also at other series than these five; no information concerning applicable dosimetry is available to us.

**Included also in PLUMBBOB.

***The "total" figures are less than the column sums because some men were present at more than one series.

Table 5

Gamma Radiation Doses (mrem) by Series
Percent of Participants and Mean Values

Series	Number with known dose	Mean dose	Percent more than 100	300	1,000	3,000	5,000
GREENHOUSE	2,099	1,291	87.6	81.7	55.9	8.2	3.0
UPSHOT-KNOTHOLE	5,741	291	10.3	9.1	7.1	3.9	1.2
CASTLE	7,595	1,493	91.3	78.7	45.2	13.6	3.7
REDWING	9,205	1,534	88.3	79.2	47.0	17.6	2.8
PLUMBBOB	9,477	538	57.1	35.9	13.4	3.8	1.4
SMOKY*	(3,440)	571	62.5	38.8	14.1	2.8	1.1
TOTAL**	32,577	934	66.1	54.1	29.3	8.8	1.7

*Included in Total PLUMBBOB.

**Includes 1,540 men with known doses present at more than one series who are counted in each.

Table 6

Observed and Expected Deaths by Cause from 1 January 1958 to 31 December 1982
Among SMOKY Participants with Known Dates of Birth

Cohort Size: 3,554

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	412	433.61	0.95		
	Causes unknown	10				
	Total known causes	402				
(E)800-999	All external causes	109	82.03	1.33	1.09	1.60
(E)800-949	Accidents	74	55.27	1.34	1.05	1.68
(E)810-823	Motor vehicle	29	29.39	0.99	0.66	1.42
(E)800-807, 825-849	Other	45	25.87	1.74	1.27	2.33
(E)950-959	Suicide	10	17.79	0.56	0.27	1.03
(E)960-978	Homicide					
(E)980-989	Acts of war	14	1.45	9.64	5.26	16.17
000-796	All diseases	293	351.58	0.83	0.74	0.93
140-209	All malignant neoplasms	77	87.78	0.88	0.69	1.10
140-149	Buccal cavity and pharynx	1	2.83	0.35	0.01	1.96
150-159	Digestive	17	20.98	0.81	0.47	1.30
160	Respiratory	26	32.00	0.81	0.53	1.19
185-187	Genital	4	3.87	1.03	0.28	2.64
188-189	Urinary	1	4.06	0.25	0.01	1.37
204-207	Leukemia and aleukemia	10	3.97	2.52	1.20	4.63
200-203, 208,209	Other lymphatic	2	6.51	0.31	0.04	1.11
170-174, 190-199	Other malignancies	16	13.57	1.18	0.67	1.91
390-448	Cardiovascular	130	180.13	0.72	0.60	0.86
430-438	Vascular lesions of CNS	19	17.86	1.06	0.64	1.66
410-413	Arteriosclerotic heart disease	93	133.46	0.70	0.56	0.85
470-486	Influenza and pneumonia	7	7.39	0.95	0.38	1.95
571	Cirrhosis	19	16.90	1.12	0.68	1.76
780-796	Symptoms, senility, etc.	8	5.87	1.36	0.59	2.69
Remainder of 000-796	Other diseases	52	53.51	0.97		

Table 7

Leukemia Deaths by Type, Radiation Dose, Year of Death, and Year of Birth

SMOKY

Cause of death	Leukemia type	Radiation dose (rem)	Year of death	Year of birth
204.0	Acute lymphatic	0.114	1960	1938
204.1	Chronic lymphatic	0.312	1979	1913
204.1*	Chronic lymphatic	0.138	1982	1896
205.0	Acute myeloid	0	1972	1911
205.0	Acute myeloid	0.105	1975	1923
205.0	Acute myeloid	0.430	1981	1932
205.0	Acute myeloid	0.130	1970	1922
205.0	Acute myeloid	1.250	1978	1934
205.1	Chronic myeloid	0.615	1976	1934
205.1	Chronic myeloid	3.627	1968	1934
207.0	Acute leukemia	0.476	1979	1926

*Not included in Table 6.

Table 8

Observed and Expected Mortality from Cancer by Calendar Year

SMOKY

Cohort Size: 3,554

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	0	12	5	17
	Expected	3.51	9.36	7.92	20.95
	SMR	-	1.28	0.63	0.81
Respiratory	Observed	6	9	11	26
	Expected	3.83	14.68	13.21	32.00
	SMR	1.57	0.61	0.83	0.81
Leukemia	Observed	1	5	4	10
	Expected	1.12	1.69	1.14	3.97
	SMR	0.89	2.96	3.51	2.52
Other	Observed	5	13	6	24
	Expected	6.54	13.60	10.51	30.86
	SMR	0.76	0.96	0.57	0.78
TOTAL	Observed	12	39	26	77
	Expected	15.00	39.33	32.78	87.78
	SMR	0.80	0.99	0.79	0.88

Table 9

Observed and Expected Mortality from Cancer by Radiation Dose

SMOKY

Cohort Size: 3,554

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100-299	300-999	1,000-2,999	3,000+	Total
Digestive	Observed	0	4	5	2	3	2	17
	Expected	0.79	9.20	4.55	3.98	1.79	0.64	20.95
	SMR	-	0.43	1.10	0.50	1.68	3.12	0.81
Respiratory	Observed	0	10	2	11	2	1	26
	Expected	1.22	14.08	6.93	5.99	2.76	1.02	32.00
	SMR	-	0.71	0.29	1.84	0.72	0.98	0.81
Leukemia	Observed	0	1	3	4	1	1	10
	Expected	0.13	1.63	0.87	0.85	0.38	0.11	3.97
	SMR	-	0.61	3.45	4.71	2.63	9.09	2.52
Other	Observed	0	10	3	8	1	0	24
	Expected	1.09	13.04	6.72	6.24	2.83	0.94	30.86
	SMR	-	0.77	0.45	1.28	0.35	-	0.78
TOTAL	Observed	3	25	13	25	7	4	77
	Expected	3.23	37.95	19.07	17.06	7.76	2.71	87.78
	SMR	0.93	0.66	0.68	1.47	0.90	1.48	0.88

Table 10

Observed and Expected Deaths by Cause from 1 January 1958 to 31 December 1982
Among PLUMBBOB (Excluding SMOKY) Participants with Known Dates of Birth*

Cohort Size: 10,131

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	1,232	1,695.99	0.73	0.69	0.77
	Causes unknown	75				
	Total known causes	1,157			0.64	0.72
(E)800-999	All external causes	230	238.22	0.97	0.84	1.10
(E)800-949	Accidents	152	159.14	0.96	0.81	1.12
(E)810-823	Motor vehicle	56	80.82	0.69	0.52	0.90
(E)800-807, 825-849	Other	96	78.32	1.23	0.99	1.50
(E)950-959	Suicide	38	54.75	0.69	0.49	0.95
(E)960-978	Homicide	22	20.10	1.09	0.69	1.66
(E)980-989	Acts of war	18	4.21	4.28	2.53	6.76
000-796	All diseases	927	1,457.77	0.64	0.60	0.68
140-209	All malignant neoplasms	272	365.04	0.75	0.66	0.84
140-149	Buccal cavity and pharynx	2	12.16	0.16	0.02	0.59
150-159	Digestive	68	90.38	0.75	0.58	0.95
160-163	Respiratory	98	137.81	0.71	0.58	0.87
185-187	Genital	19	17.04	1.12	0.67	1.74
188-189	Urinary	9	17.62	0.51	0.23	0.97
204-207	Leukemia and aleukemia	13	14.60	0.89	0.47	1.52
200-203, 208,209	Other lymphatic	9	24.01	0.37	0.17	0.71
170-174, 190-199	Other malignancies	54	51.44	1.05	0.79	1.37
390-448	Cardiovascular	465	768.57	0.61	0.55	0.66
430-438	Vascular lesions of CNS	47	76.69	0.61	0.45	0.81
410-413	Arteriosclerotic heart disease	355	572.80	0.62	0.56	0.69
470-486	Influenza and pneumonia	13	29.59	0.44	0.23	0.75
571	Cirrhosis	43	61.75	0.70	0.50	0.94
780-796	Symptoms, senility, etc.	10	21.87	0.46	0.22	0.84
Remainder of 000-796	Other diseases	124	210.95	0.59	0.49	0.70

*SMOKY participants excluded.

Table 11

Observed and Expected Mortality from Cancer by Calendar Year

PLUMBBOB (Excluding SMOKY)

Cohort Size: 10,131

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	6	30	32	68
	Expected	15.32	40.40	34.71	90.38
	SMR	0.39	0.74	0.92	0.75
Respiratory	Observed	9	40	49	98
	Expected	17.50	63.78	56.81	137.81
	SMR	0.51	0.63	0.86	0.71
Leukemia	Observed	2	6	5	13
	Expected	3.77	6.24	4.60	14.60
	SMR	0.53	0.96	1.09	0.89
Other	Observed	18	38	37	93
	Expected	24.17	54.42	43.88	122.25
	SMR	0.74	0.70	0.84	0.76
TOTAL	Observed	35	114	123	272
	Expected	60.86	164.84	140.00	365.04
	SMR	0.58	0.69	0.88	0.75

Table 12

Observed and Expected Mortality from Cancer by Radiation Dose

PLUMBBOB (Excluding SMOKY)

Cohort Size: 10,131

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100–299	300–999	1,000–2,999	3,000+	Total
Digestive	Observed	21	21	8	13	4	2	68
	Expected	25.30	30.82	13.71	14.82	4.00	1.73	90.38
	SMR	0.83	0.68	0.58	0.88	1.00	1.16	0.75
Respiratory	Observed	32	34	8	18	1	5	98
	Expected	38.55	46.90	21.07	22.53	6.15	2.63	137.81
	SMR	0.83	0.72	0.38	0.80	0.16	1.90	0.71
Leukemia	Observed	5	3	1	4	0	0	13
	Expected	4.71	4.61	2.06	2.20	0.69	0.33	14.60
	SMR	1.06	0.65	0.49	1.82	–	–	0.89
Other	Observed	29	26	10	24	6	0	93
	Expected	36.78	40.19	17.98	19.26	5.56	2.49	122.25
	SMR	0.79	0.65	0.56	1.25	1.08	–	0.76
TOTAL	Observed	84	84	27	59	11	7	272
	Expected	105.34	122.52	54.80	58.81	16.40	7.18	365.04
	SMR	0.80	0.69	0.49	1.00	0.67	0.97	0.75

Table 13

Observed and Expected Deaths by Cause from 1 January 1954 to 31 December 1982
Among UPSHOT-KNOTHOLE Participants with Known Dates of Birth

Cohort Size: 9,694

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	1,175	1,446.23	0.81		
	Causes unknown	77				
	Total known causes	1,098				
(E)800-999	All external causes	270	256.44	1.05	0.93	1.19
(E)800-949	Accidents	178	175.20	1.02	0.87	1.18
(E)810-823	Motor vehicle	74	90.87	0.81	0.64	1.02
(E)800-807, 825-949	Other	104	84.31	1.23	1.01	1.49
(E)950-959	Suicide	43	55.95	0.77	0.56	1.04
(E)960-978	Homicide	31	21.28	1.46	0.99	2.07
(E)980-989	Acts of war	18	4.01	4.49	2.66	7.09
000-796	All diseases	828	1,189.79	0.70	0.65	0.74
140-209	All malignant neoplasms	248	295.93	0.84	0.74	0.95
140-149	Buccal cavity and pharynx	8	9.75	0.82	0.35	1.62
150-159	Digestive	51	70.77	0.72	0.54	0.95
160-163	Respiratory	94	108.84	0.86	0.70	1.06
185-187	Genital	16	12.63	1.27	0.72	2.06
188-189	Urinary	7	13.75	0.51	0.20	1.05
204-207	Leukemia and aleukemia	13	13.20	0.98	0.52	1.68
200-203, 208,209	Other lymphatic	18	21.69	0.83	0.49	1.31
170-174, 190-199	Other malignancies	41	45.29	0.91	0.65	1.23
390-448	Cardiovascular	370	612.46	0.60	0.54	0.67
430-438	Vascular lesions of CNS	40	60.25	0.66	0.47	0.90
410-413	Arteriosclerotic heart disease	267	453.35	0.59	0.52	0.66
470-486	Influenza and pneumonia	25	24.85	1.01	0.65	1.49
571	Cirrhosis	58	57.32	1.01	0.77	1.31
780-796	Symptoms, senility, etc.	16	19.38	0.83	0.47	1.34
Remainder of 000-796	Other diseases	111	179.85	0.62		

Table 14

Observed and Expected Mortality from Cancer by Calendar Year

UPSHOT-KNOTHOLE

Cohort Size: 9,694

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	0	12	39	51
	Expected	7.05	20.64	43.03	70.72
	SMR	-	0.58	0.91	0.72
Respiratory	Observed	2	17	75	94
	Expected	6.31	29.62	72.83	108.84
	SMR	0.32	0.57	1.03	0.86
Leukemia	Observed	2	4	7	13
	Expected	2.86	4.22	6.13	13.20
	SMR	0.70	0.95	1.14	0.98
Other	Observed	11	23	56	90
	Expected	14.89	31.37	56.80	103.17
	SMR	0.74	0.73	0.99	0.87
TOTAL	Observed	15	56	177	248
	Expected	31.11	85.85	178.79	295.93
	SMR	0.48	0.65	1.01	0.84

Table 15

Observed and Expected Mortality from Cancer by Radiation Dose

UPSHOT-KNOTHOLE

Cohort Size: 9,694

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100-299	300-999	1,000-2,999	3,000+	Total
Digestive	Observed	17	31	0	0	3	0	51
	Expected	25.99	39.02	0.72	1.30	1.60	2.09	70.72
	SMR	0.65	0.79	-	-	1.88	-	0.72
Respiratory	Observed	28	58	3	2	0	3	94
	Expected	40.20	59.88	1.10	1.89	2.53	3.24	108.84
	SMR	0.70	0.97	2.72	1.06	-	0.93	0.86
Leukemia	Observed	5	6	0	2	0	0	13
	Expected	5.08	7.17	0.12	0.21	0.27	0.35	13.20
	SMR	0.98	1.20	-	9.70	-	-	0.98
Other	Observed	35	47	3	1	1	3	90
	Expected	38.84	56.39	0.96	1.74	2.23	3.01	103.17
	SMR	0.90	0.83	3.12	0.57	0.44	1.00	0.87
TOTAL	Observed	85	142	6	5	4	6	248
	Expected	110.11	162.46	2.90	5.14	6.63	8.69	295.93
	SMR	0.77	0.87	2.07	0.97	0.60	0.69	0.84

Table 16

Observed and Expected Deaths by Cause from 1 January 1952 to 31 December 1982
Among GREENHOUSE Participants with Known Dates of Birth

Cohort Size: 2,947

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	410	494.11	0.83		
	Causes unknown	18				
	Total known causes	392				
(E)800-999	All external causes	101	82.91	1.22	0.99	1.48
(E)800-949	Accidents	61	57.00	1.07	0.82	1.37
(E)810-823	Motor vehicle	33	29.19	1.13	0.78	1.59
(E)800-807, 825-949	Other	28	27.80	1.01	0.67	1.46
(E)950-959	Suicide	21	18.24	1.15	0.71	1.76
(E)960-978	Homicide	3	6.46	1.24	0.53	2.44
(E)980-989	Acts of war	11	1.21	9.06	4.52	16.22
000-796	All diseases	291	411.20	0.71	0.63	0.79
140-209	All malignant neoplasms	76	102.76	0.74	0.58	0.93
140-149	Buccal cavity and pharynx	2	3.46	0.58	0.07	2.08
150-159	Digestive	21	24.70	0.85	0.53	1.30
160-163	Respiratory	31	38.48	0.81	0.55	1.14
185-187	Genital	2	4.08	0.49	0.06	1.77
188-189	Urinary	3	4.75	0.63	0.13	1.84
204-207	Leukemia and aleukemia	1	4.43	0.23	0.01	1.26
200-203, 208,209	Other lymphatic	6	7.35	0.82	0.30	1.78
170-174, 190-199	Other malignancies	10	15.50	0.65	0.31	1.19
390-448	Cardiovascular	141	211.98	0.67	0.56	0.78
430-438	Vascular lesions of CNS	16	19.97	0.80	0.46	1.30
410-413	Arteriosclerotic heart disease	98	157.86	0.62	0.50	0.76
470-486	Influenza and pneumonia	6	3.41	0.71	0.26	1.55
571	Cirrhosis	17	19.72	0.86	0.50	1.38
780-796	Symptoms, senility, etc.	6	6.56	0.91	0.33	1.99
Remainder of 000-796	Other diseases	45	61.77	0.73		

Table 17

Observed and Expected Mortality from Cancer by Calendar Year

GREENHOUSE

Cohort Size: 2,947

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	1	4	16	21
	Expected	1.82	5.82	17.07	24.70
	SMR	0.55	0.69	0.94	0.85
Respiratory	Observed	1	1	29	31
	Expected	1.47	7.97	29.05	38.48
	SMR	0.68	0.13	1.00	0.81
Leukemia	Observed	0	0	1	1
	Expected	0.84	1.22	2.36	4.43
	SMR	-	-	0.42	0.23
Other	Observed	0	4	19	23
	Expected	4.15	8.87	22.13	35.15
	SMR	-	0.45	0.86	0.65
TOTAL	Observed	2	9	65	76
	Expected	8.28	23.88	70.61	102.76
	SMR	0.24	0.38	0.92	0.74

Table 18

Observed and Expected Mortality from Cancer by Radiation Dose

GREENHOUSE

Cohort Size: 2,947

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100–299	300–999	1,000–2,999	3,000+	Total
Digestive	Observed	8	0	0	5	8	0	21
	Expected	7.70	2.31	1.02	4.17	7.40	2.10	24.70
	SMR	1.04	–	–	1.20	1.08	–	0.85
Respiratory	Observed	8	3	1	5	13	1	31
	Expected	11.87	3.61	1.60	6.53	11.72	3.16	38.48
	SMR	0.67	0.83	0.63	0.77	1.11	0.32	0.81
Leukemia	Observed	1	0	0	0	0	0	1
	Expected	1.34	0.41	0.18	0.78	1.39	0.33	4.43
	SMR	0.75	–	–	–	–	–	0.23
Other	Observed	6	3	1	3	6	4	23
	Expected	10.75	3.25	1.45	6.05	10.84	2.80	35.15
	SMR	0.56	0.92	0.69	0.50	0.55	1.43	0.65
TOTAL	Observed	23	6	2	13	27	5	76
	Expected	31.66	9.58	4.25	17.53	31.35	8.39	102.76
	SMR	0.73	0.63	0.47	0.74	0.86	0.60	0.74

Table 19

Observed and Expected Deaths by Cause from 1 January 1955 to 31 December 1982
Among CASTLE Participants with Known Dates of Birth

Cohort Size: 11,309

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	1,129	1,249.33	0.90		
	Causes unknown	58				
	Total known causes	1,071				
(E)800-999	All external causes	315	289.56	1.09	0.97	1.21
(E)800-949	Accidents	237	198.99	1.19	1.04	1.35
(E)810-823	Motor vehicle	123	107.35	1.15	0.95	1.37
(E)800-807, 825-949	Other	114	91.63	1.24	1.03	1.49
(E)950-959	Suicide	50	60.11	0.83	0.62	1.10
(E)960-978	Homicide	18	25.79	0.70	0.41	1.10
(E)980-989	Acts of war	10	4.67	2.14	1.02	3.94
000-796	All diseases	756	959.77	0.79	0.73	0.85
140-209	All malignant neoplasms	220	240.51	0.91	0.80	1.04
140-149	Buccal cavity and pharynx	10	7.70	1.30	0.62	2.39
150-159	Digestive	45	54.37	0.83	0.60	1.11
160-163	Respiratory	86	85.83	1.00	0.80	1.24
185-187	Genital	6	8.76	0.68	0.25	1.49
188-189	Urinary	8	10.49	0.76	0.33	1.50
204-207	Leukemia and aleukemia	14	12.22	1.15	0.63	1.92
200-203, 208,209	Other lymphatic	13	20.11	0.65	0.34	1.11
170-174, 190-199	Other malignancies	38	41.01	0.93	0.66	1.27
390-448	Cardiovascular	372	474.17	0.78	0.71	0.87
430-438	Vascular lesions of CNS	34	44.48	0.76	0.53	1.07
410-413	Arteriosclerotic heart disease	286	350.42	0.82	0.72	0.92
470-486	Influenza and pneumonia	13	20.46	0.64	0.34	1.09
571	Cirrhosis	53	54.19	0.98	0.73	1.28
780-796	Symptoms, senility, etc.	9	17.68	0.51	0.23	0.97
Remainder of 000-796	Other diseases	89	152.76	0.58		

Table 20

Observed and Expected Mortality from Cancer by Calendar Year

CASTLE

Cohort Size: 11,309

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	4	16	25	45
	Expected	5.29	16.67	32.41	54.37
	SMR	0.76	0.96	0.77	0.83
Respiratory	Observed	1	22	63	86
	Expected	4.48	24.55	56.80	85.83
	SMR	0.22	0.90	1.11	1.00
Leukemia	Observed	2	5	7	14
	Expected	3.08	4.12	5.02	12.22
	SMR	0.65	1.21	1.39	1.15
Other	Observed	7	22	46	75
	Expected	14.74	28.59	44.76	88.09
	SMR	0.47	0.77	1.03	0.85
TOTAL	Observed	14	65	141	220
	Expected	27.59	73.93	138.99	240.51
	SMR	0.51	0.88	1.01	0.91

Table 21

Observed and Expected Mortality from Cancer by Radiation Dose

CASTLE

Cohort Size: 11,309

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100-299	300-999	1,000-2,999	3,000+	Total
Digestive	Observed	17	1	5	9	12	1	45
	Expected	16.83	4.00	4.41	11.78	11.74	5.61	54.37
	SMR	1.01	0.25	1.13	0.76	1.02	0.18	0.83
Respiratory	Observed	32	4	6	17	19	8	86
	Expected	26.69	2.06	7.00	18.66	18.59	12.83	85.83
	SMR	1.20	1.94	0.86	0.91	1.02	0.62	1.00
Leukemia	Observed	5	3	2	0	3	1	14
	Expected	3.89	0.81	1.01	2.71	2.62	1.18	12.22
	SMR	1.29	3.70	1.98	-	1.15	0.85	1.15
Other	Observed	28	6	9	18	10	4	75
	Expected	27.72	10.09	7.23	19.34	18.95	4.76	88.09
	SMR	1.01	0.59	1.24	0.93	0.53	0.84	0.85
TOTAL	Observed	82	14	22	44	44	14	220
	Expected	75.13	16.96	19.65	52.49	51.90	24.38	240.51
	SMR	1.09	0.83	1.12	0.84	0.85	0.57	0.91

Table 22

Observed and Expected Deaths by Cause from 1 January 1957 to 31 December 1982
Among REDWING Participants with Known Dates of Birth

Cohort Size: 10,202

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	966	1,092.60	0.88		
	Causes unknown	45				
	Total known causes	921				
(E)800-999	All external causes	244	246.15	0.99	0.87	1.12
(E)800-949	Accidents	169	167.86	1.01	0.86	1.17
(E)810-823	Motor vehicle	72	91.28	0.79	0.62	0.99
(E)800-807, 825-949	Other	97	76.57	1.27	1.03	1.55
(E)950-959	Suicide	40	51.35	0.78	0.56	1.06
(E)960-978	Homicide	26	22.73	1.14	0.75	1.68
(E)980-989	Acts of war	9	4.21	2.14	0.98	4.06
000-796	All diseases	677	846.45	0.80	0.74	0.86
140-209	All malignant neoplasms	203	212.28	0.96	0.83	1.10
140-149	Buccal cavity and pharynx	10	6.78	1.48	0.71	2.71
150-159	Digestive	44	48.89	0.90	0.65	1.21
160-163	Respiratory	68	76.00	0.89	0.69	1.13
185-187	Genital	16	8.35	1.92	1.09	3.11
188-189	Urinary	6	9.38	0.64	0.23	1.39
204-207	Leukemia and aleukemia	8	10.46	0.76	0.33	1.51
200-203, 208,209	Other lymphatic	13	17.19	0.76	0.40	1.29
170-174, 190-199	Other malignancies	38	35.24	1.08	0.76	1.48
390-448	Cardiovascular	320	421.70	0.76	0.68	0.85
430-438	Vascular lesions of CNS	22	40.27	0.55	0.34	0.83
410-413	Arteriosclerotic heart disease	260	311.85	0.83	0.74	0.94
470-486	Influenza and pneumonia	13	18.21	0.71	0.38	1.22
571	Cirrhosis	42	45.40	0.93	0.67	1.25
780-796	Symptoms, senility, etc.	11	15.32	0.72	0.36	1.29
Remainder of 000-796	Other diseases	88	133.54	0.66		

Table 23

Observed and Expected Mortality from Cancer by Calendar Year

REDWING

Cohort Size: 10,202

Kind of cancer	Deaths	Follow-up year 1-10	11-20	21+	Total
Digestive	Observed	4	18	22	44
	Expected	6.24	18.96	23.69	48.89
	SMR	0.64	0.95	0.93	0.90
Respiratory	Observed	7	20	41	68
	Expected	6.10	29.38	40.52	76.00
	SMR	1.15	0.68	1.01	0.89
Leukemia	Observed	3	3	2	8
	Expected	2.87	4.06	3.53	10.46
	SMR	1.05	0.74	0.57	0.76
Other	Observed	18	34	31	83
	Expected	14.83	30.02	32.08	76 3
	SMR	1.21	1.13	0.97	1.08
TOTAL	Observed	32	75	96	203
	Expected	30.04	82.42	99.82	212.28
	SMR	1.07	0.91	0.96	0.96

Table 24

Observed and Expected Mortality from Cancer by Radiation Dose

REDWING

Cohort Size: 10,202

Kind of cancer	Deaths	Radiation dose (mrem)						
		Unknown	Less than 100	100-299	300-999	1,000-2,999	3,000+	Total
Digestive	Observed	3	5	5	11	16	4	44
	Expected	4.03	6.99	3.86	13.11	12.45	8.45	48.89
	SMR	0.74	0.72	1.30	0.84	1.28	0.47	0.90
Respiratory	Observed	3	8	7	21	12	17	68
	Expected	6.27	10.76	6.03	20.38	19.35	13.21	76.00
	SMR	0.48	0.74	1.16	1.03	0.62	1.29	0.89
Leukemia	Observed	1	3	0	1	1	2	8
	Expected	0.94	1.29	0.84	2.93	2.72	1.74	10.46
	SMR	1.07	2.32	-	0.34	0.37	1.15	0.76
Other	Observed	11	10	3	27	21	11	83
	Expected	6.63	10.17	6.13	21.13	19.81	13.06	76.93
	SMR	1.66	0.98	0.49	1.28	1.06	0.84	1.08
TOTAL	Observed	18	26	15	60	50	34	203
	Expected	17.87	29.21	16.86	57.55	54.33	36.46	212.28
	SMR	1.01	0.89	0.89	1.04	0.92	0.93	0.96

Table 25

Observed and Expected Deaths by Cause Among Nuclear Test Participants

ALL SERIES

Cohort Size: 46,186*

ICDA Code 8th Rev.	Cause of death	Mortality Obs.	Mortality Exp.**	SMR	95-percent confidence interval Lower limit	95-percent confidence interval Upper limit
000-(E)999	All causes	5,113*	6,125.36	0.83		
	Causes unknown	272				
	Total known causes	4,841			0.77	0.81
(E)800-999	All external causes	1,216	1,152.36	1.06	1.00	1.12
(E)800-949	Accidents	833	784.38	1.06	0.99	1.14
(E)810-823	Motor vehicle	376	414.20	0.91	0.82	1.00
(E)800-807, 825-949	Other	457	370.15	1.23	1.12	1.35
(E)950-959	Suicide	194	248.46	0.78	0.67	0.90
(E)960-978	Homicide	112	100.45	1.11	0.92	1.34
(E)980-989	Acts of war	77	19.07	4.04	3.19	5.05
000-796	All diseases	3,625	4,973.00	0.73	0.71	0.75
140-209	All malignant neoplasms	1,046	1,243.54	0.84	0.79	0.89
140-149	Buccal cavity and pharynx	31	40.64	0.76	0.52	1.08
150-159	Digestive	237	295.17	0.80	0.70	0.91
160-163	Respiratory	382	456.11	0.84	0.76	0.93
185-187	Genital	58	52.13	1.11	0.84	1.44
188-189	Urinary	34	57.17	0.59	0.41	0.83
204-207	Leukemia and aleukemia	56	56.37	0.99	0.75	1.29
200-203, 208,209	Other lymphatic	59	92.72	0.64	0.48	0.82
170-174, 190-199	Other malignancies	189	193.23	0.98	0.84	1.13
390-448	Cardiovascular	1,723	2,541.50	0.68	0.65	0.71
430-438	Vascular lesions of CNS	170	247.10	0.69	0.59	0.80
410-413	Arteriosclerotic heart disease	1,300	1,884.76	0.69	0.65	0.73
470-486	Influenza and pneumonia	77	103.92	0.74	0.58	0.93
571	Cirrhosis	225	244.35	0.92	0.80	1.05
780-796	Symptoms, senility, etc.	55	82.95	0.66	0.50	0.86
Remainder of 000-796	Other diseases	499	756.74	0.66		

*Numbers are less than the sums of corresponding numbers for individual series because there were 1,651 multiple test participants.

**Calculated from age- and time-specific U.S. white male death rates.

Table 26

Observed and Expected Mortality for Certain Groups of Causes by Follow-up Period

ALL SERIES

Cohort Size: 46,186*

Cause of death	Deaths	Follow-up period in years ≤10	11-20	21+	Total
All disease	Observed	395	1321	1909	3625*
	Expected	764.31	1933.07	2275.62	4973.00
	SMR	0.52	0.68	0.84	0.73
Malignant Neoplasms					
All	Observed	108	345	593	1046
	Expected	166.33	451.16	626.05	1243.54
	SMR	0.65	0.76	0.95	0.84
Digestive system	Observed	15	90	132	237
	Expected	37.77	107.16	150.25	295.18
	SMR	0.40	0.84	0.88	0.80
Respiratory system	Observed	25	107	250	382
	Expected	38.21	163.02	254.89	456.11
	SMR	0.65	0.66	0.98	0.84
Genital system	Observed	6	17	35	58
	Expected	9.40	16.96	25.77	52.13
	SMR	0.64	1.00	1.36	1.11
Urinary system	Observed	3	9	22	34
	Expected	6.03	20.74	30.39	57.17
	SMR	0.50	0.43	0.72	0.59
Leukemia and aleukemia	Observed	10	22	24	56
	Expected	14.02	20.72	21.64	56.37
	SMR	0.71	1.06	1.11	0.99
Other lymphatic	Observed	10	24	25	59
	Expected	22.20	35.51	35.02	92.72
	SMR	0.45	0.68	0.71	0.64
Other malignancies	Observed	39	76	105	220
	Expected	38.70	87.05	108.09	233.84
	SMR	1.01	0.87	0.97	0.94

*Numbers are less than the sums of corresponding numbers for individual series because there were 1,651 multiple test participants.

Table 26 (continued)

Cause of death	Deaths	Follow-up period in years ≤10	11–20	21+	Total
Cardiovascular disease	Observed	191	652	880	1723
	Expected	365.89	1002.33	1173.28	2541.50
	SMR	0.52	0.65	0.75	0.68
Cirrhosis of liver	Observed	16	92	117	225
	Expected	32.23	107.54	104.59	244.36
	SMR	0.50	0.86	1.12	0.92
Other disease	Observed	80	232	319	631
	Expected	199.86	372.04	371.70	943.60
	SMR	0.40	0.62	0.86	0.67

Table 27

Observed and Expected Mortality for Certain Groups of Causes by Reported Radiation Dose

ALL SERIES

Cohort Size: 46,186*

Cause of death	Deaths	Radiation dose (mrem)						
		Unknown	<100	100-299	300-999	1,000-2,999	3,000+	Total
All disease	Observed	966	1,037	323	638	458	203	3,625*
	Expected	1,356.77	1,486.69	452.91	798.19	605.36	273.08	4,973.00
	SMR	0.71	0.70	0.71	0.80	0.76	0.74	0.73
Malignant Neoplasms								
All	Observed	293	293	80	196	125	59	1,046
	Expected	339.32	370.71	113.64	199.70	151.88	68.29	1,243.54
	SMR	0.86	0.79	0.70	0.98	0.82	0.86	0.84
Digestive system	Observed	65	61	23	38	41	9	237
	Expected	79.66	90.34	27.30	46.95	35.02	15.90	295.17
	SMR	0.82	0.68	0.84	0.81	1.17	0.57	0.80
Respiratory system	Observed	103	117	26	69	39	28	382
	Expected	123.27	138.23	42.24	72.68	54.88	24.81	456.11
	SMR	0.84	0.85	0.62	0.95	0.71	1.13	0.84
Genital system	Observed	10	20	4	14	7	3	58
	Expected	13.92	16.64	4.84	8.27	5.79	2.67	52.13
	SMR	0.72	1.20	0.83	1.69	1.21	1.12	1.11
Urinary system	Observed	10	10	1	7	4	2	34
	Expected	15.38	17.61	5.30	9.09	6.73	3.06	57.17
	SMR	0.65	0.57	0.19	0.77	0.59	0.65	0.59

*Numbers are less than the sums of corresponding numbers for individual series because there were 1,651 multiple test participants.

Table 27 (continued)

Cause of death	Deaths	Radiation dose (mrem) Unknown	<100	100-299	300-999	1,000-2,999	3,000+	Total
Malignant Neoplasms (cont'd.)								
Leukemia and aleukemia	Observed	16	16	5	10	5	4	56
	Expected	15.91	15.62	4.93	9.30	7.37	3.24	56.37
	SMR	1.01	1.02	1.01	1.08	0.68	1.23	0.99
Other lymphatic	Observed	19	13	1	17	9	0	59
	Expected	26.13	25.67	8.14	15.28	12.16	5.34	92.72
	SMR	0.73	0.51	0.12	1.11	0.74	-	0.64
Other malignant neoplasms	Observed	70	56	20	41	20	13	220
	Expected	65.05	66.58	20.89	38.13	29.93	13.29	233.87
	SMR	1.08	0.84	0.96	1.08	0.67	0.98	0.94
Cardiovascular disease	Observed	439	488	174	300	222	100	1,723
	Expected	687.26	775.55	233.57	404.95	302.50	137.67	2,541.50
	SMR	0.64	0.63	0.74	0.74	0.73	0.73	0.68
Other disease	Observed	234	256	69	142	111	44	856
	Expected	330.19	340.43	105.65	193.54	150.98	67.17	1,187.96
	SMR	0.71	0.75	0.65	0.73	0.74	0.66	0.72

Appendix A

Leukemia Deaths by Type, Radiation Dose, Year of Death, and Year of Birth

Cause of death	Leukemia type	Radiation dose (rem)	Year of death	Year of birth
		SMOKY		
204.0	Acute lymphatic	0.114	1960	1938
204.1	Chronic lymphatic	0.312	1979	1913
204.1*	Chronic lymphatic	0.138	1982	1896
205.0	Acute myeloid	0	1972	1911
205.0	Acute myeloid	0.105	1975	1923
205.0	Acute myeloid	0.430	1981	1932
205.0	Acute myeloid	0.130	1970	1922
205.0	Acute myeloid	1.250	1978	1934
205.1	Chronic myeloid	0.615	1976	1934
205.1	Chronic myeloid	3.627	1968	1934
207.0	Acute leukemia	0.476	1979	1926
		OTHER PLUMBBOB		
204.1	Chronic lymphatic	0	1980	1915
205.0	Acute myeloid	0.380	1972	1924
205.0	Acute myeloid	0.420	1976	1907
205.0	Acute myeloid	0.033	1963	1903
205.1	Chronic myeloid	0	1975	1924
205.1	Chronic myeloid	Unknown	1975	1923
205.1	Chronic myeloid	Unknown	1981	1939
205.1**	Chronic myeloid	Unknown	1976	1929
205.1	Chronic myeloid	0.500	1976	1906

Cause of death	Leukemia type	Radiation dose (rem)	Year of death	Year of birth
	OTHER PLUMBBOB (continued)			
207.0**	Acute leukemia	0.120	1981	1918
207.0	Acute leukemia	Unknown	1958	1927
207.9	Unspecified	0.475	1972	1911
207.9	Unspecified	Unknown	1979	1931
	UPSHOT-KNOTHOLE			
204.0	Acute lymphatic	0	1955	1904
204.0	Acute lymphatic	0	1981	1931
204.1	Chronic lymphatic	0	1978	1917
204.1	Chronic lymphatic	Unknown	1961	1920
205.0	Acute myeloid	Unknown	1979	1932
205.0	Acute myeloid	0	1967	1903
205.1	Chronic myeloid	0.360	1974	1929
205.1	Chronic myeloid	Unknown	1976	1930
206.0	Acute monocytic	0	1969	1932
206.9	Unspecified monocytic	0	1976	1917
207.0	Acute leukemia	Unknown	1976	1929
207.9	Unspecified	Unknown	1970	1921
207.9***	Unspecified	0.595	1967	1918
	GREENHOUSE			
205.0	Acute myeloid	Unknown	1978	1930

Cause of death	Leukemia type	Radiation dose (rem)	Year of death	Year of birth
		CASTLE		
204.0	Acute lymphatic	1.400	1966	1931
204.1	Chronic lymphatic	0.200	1972	1929
204.1	Chronic lymphatic	0	1975	1930
205.0	Acute myeloid	Unknown	1969	1926
205.0	Acute myeloid	0	1974	1933
205.0	Acute myeloid	1.935	1955	1930
205.1	Chronic myeloid	Unknown	1963	1920
205.1	Chronic myeloid	6.185	1965	1934
205.1**	Chronic myeloid	Unknown	1976	1929
205.1	Chronic myeloid	0	1979	1934
207.0**	Acute leukemia	0.120	1981	1918
207.0	Acute leukemia	Unknown	1982	1930
207.9	Unspecified	1.925	1978	1933
207.9	Unspecified	Unknown	1975	1933
		REDWING		
204.0	Acute lymphatic	0	1960	1934
204.0	Acute lymphatic	Unknown	1963	1936
205.0	Acute myeloid	2.995	1975	1922
205.0	Acute myeloid	3.935	1972	1913
205.0	Acute myeloid	0	1964	1926
207.0	Acute leukemia	0	1981	1917
207.0	Acute leukemia	3.155	1982	1916
207.9***	Unspecified	0.595	1967	1918

*Not included in Table 25. Over 85 years of age at death.
**Participated at both CASTLE and PLUMBBOB.
***Participated at UPSHOT-KNOTHOLE and REDWING.

APPENDIX B

BEST AVAILABLE COPY

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.C.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
UNK	N	10	75	77	18	58	45	272
0112	N			1	1			2
0119	N	1	3	4		2		9
0189	N					1		1
0380	N						1	1
0388	N	1						1
0389	N		2	5	1	2	3	13
0399	N		1	2				3
065	N		1					1
070	N			1		2	1	3
1178	N	1						1
1179	N			1				1
135	N				1			1
136	N			1				1
1409	N			1				1
1410	N					1	1	2
1419	N			1			1	2
1420	N						1	1
1428	N					1		1
144	N					1		1
1450	N			1				1
1451	N					1		1
1459	N	1	1			1		3
1460	N		1	2			2	5
147	N				1	2		3
1481	N						1	1
1489	N			1				1
149	N			2	1	3	4	8
150	N	4	8	6	3	4	7	30
1519	N	1	9	6	5	7	10	33
1520	N			1				1
1529	N		1				1	2
1530	N		2	4			2	8
1531	N			1			1	2
1533	N		1			2	1	4
1538	N	4	24	14	3	13	8	66
1539	N					1	2	3
1540	N			2				2
1541	N	2	3	3	2	3	3	16
1550	N	1	2	1	1	1	2	7
1551	N				1	1		2
1560	N			1			1	2
1561	N		3					3
1570	N		1			1		2

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GK	CA	RE	TOTAL* COHORT
1576	N	1	1					2
1579	N	3	12	12	6	9	6	47
1580	N	1	1			1		3
1589	N					2		2
1608	N						1	1
1618	N			1				1
1619	N		4	4	2	1	2	13
1621	N	26	93	88	28	85	64	363
1630	N		1					1
1631	N			1	1		1	3
1701	N			2		1		3
1702	N		2					2
1706	N		1		1			2
1707	N			1		1		2
1709	N		1				1	2
1711	N					1		1
1719	N		1				1	2
1723	N				1	1		1
1726	N					1		1
1727	N					1		1
1729	N	5	12	4	1	9	9	39
1733	N				1			1
174	N	1		1				2
1830	N						1	1
185	N	3	16	14	2	3	11	45
186	N		2	1		3	4	9
1870	N	1	1	1				3
188	N		2	2	1	3	1	9
1890	N	1	6	5	2	5	5	24
1899	N		1					1
191	N	2	7	8		7	4	28
1929	N	1	5	2			7	13
193	N			1	1			2
1940	N		1					1
1942	N	1		1				2
1950	N					1		1
1959	N	1	4	1		2	2	8
1970	N			1				1
1977	N		2	1	1		1	5
1978	N	2	1			1	1	5
1983	N		1					1
1984	N			1				1
1990	N	2	14	14	4	11	11	54
1991	N	1	2	3		1	1	8

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GK=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GH	CA	RE	TOTAL* COHORT
2000	N		5			1	3	8
2001	N		1	3		6	2	12
201	N	2	3	4		1	5	15
2020	N		1	1				1
2022	N			4	3	3	3	13
203	N		3	6	3	3	2	16
2040	N	1		2		1	2	6
2041	N	1	1	2		2		6
2050	N	5	3	2	1	3	3	17
2051	N	2	5	2		4		12
2060	N			1				1
2069	N			1				1
2070	N	1	2	1		2	2	7
2079	N		2	2		2	1	6
208	N		1				1	2
2114	N						1	1
2259	N		1					1
228	N					1		1
2381	N	2	3	2	1	3	1	12
2384	N						1	1
2422	N			1				1
2500	N	2	1	2				5
2509	N	4	4	3	4	9	4	26
2551	N			1				1
2589	N						1	1
260	N					1		1
2699	N		1	1				2
2738	N		1					1
276	N		2				1	3
277	N					2	1	3
279	N	1	1				1	3
2825	N				1			1
284	N		1	2			1	4
2871	N					1	1	1
288	N				1	1		2
2901	N		1					1
2910	N				1	3	1	5
3032	N	2	4	3		5	4	18
3039	N	3	5	4	3	4	4	23
3049	N						1	1
3201	N	1	1					2
3208	N	1						1
321	N		1					1
3310	N	1						1

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GH=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
340	N		3					3
3406	N		1					1
342	N			1				1
3443	N						1	1
3452	N	1						1
3459	N		1			1	1	3
3479	N		2	1				3
3480	N	1	2	2			1	6
3482	N		1					1
350	N			1				1
3506	N		1					1
354	N			1		1		2
3940	N		2			1		3
3949	N		1					1
3950	N		3	1				4
3959	N		5	3		3		11
3960	N			1		1		2
3979	N			2		1		3
398	N			2		1	1	4
4000	N						1	1
4003	N					1		1
402	N		1	4	2	3	4	14
404	N				1			1
4100	N	7	15	12	6	15	8	57
4109	N	52	224	160	67	184	154	806
4110	N		1					1
4119	N	1	3	3		2	4	13
4121	N	2	7	4	1	4	4	19
4122	N	4	12	9		6	8	38
4123	N	22	73	62	19	56	64	285
4124	N	5	20	17	5	19	16	81
4210	N	1	1			3		5
4219	N					1		1
422	N	1		1				1
423	N		1					1
4241	N						1	1
4249	N						1	1
425	N		1	7	2	6	2	18
426	N	1	1					2
4270	N		4	7	3	5	3	22
4272	N	3	12	6	6	2	5	33
4273	N		1					1
4274	N		1					1
4276	N					1		1

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
4279	N	1	3	1	1	2	1	7
428	N	1	4	2	2	3		11
4290	N			2				2
4299	N	2	7	8	2	7	6	30
4300	N			3	1	1		5
4309	N	2	11	11	2	8	4	35
4310	N	3	1	2		2	1	9
4319	N	5	6	5	6	8	8	38
4320	N		1					1
4329	N		1	1	2			4
4339	N	2	7	7		5	4	24
4349	N			1				1
4360	N	1	3	1	1	1	2	9
4369	N	5	10	7	3	7	1	32
4370	N						1	1
4379	N	1	4	1		1		7
4389	N		3	1	1	1	1	4
4402	N		1				1	2
4409	N		2	2	2	2	3	11
4410	N	3	1	7			2	13
4411	N	1	2			3	3	9
4412	N	3	4	3	2	2		14
4419	N	1	2	2			1	6
442	N				1	2	2	4
4439	N			1				1
4442	N			1	1	1	1	4
4443	N		1					1
4460	N		1			1		2
4463	N				1			1
447	N		1		1		1	3
450	N	3	7	1	2	4	4	21
4510	N					2	1	3
4519	N				1			1
453	N						1	1
4560	N	1	2	1		2	1	7
4580	N			1				1
4589	N			1				1
471	N				1	1		2
480	N		1	1	1		1	4
481	N		3	2	1		1	7
4820	N	1		1				2
4823	N			2				2
4829	N		1					1
485	N	4	1	10	2	3	6	26

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
486	N	2	7	8	1	9	4	31
4860	N			1			1	2
490	N		1					1
491	N	2	2				3	7
492	N	3	13	11	2	4	5	36
493	N		1	1		1	2	4
5082	N					1		1
510	N		1	1				2
513	N	1	1	1		1		4
514	N	1	1	1				3
517	N		1		1	1		3
518	N		2			1		3
5190	N						1	1
5191	N				1			1
5192	N		2					2
5193	N	5	9	10	3	7	4	38
5304	N					1		1
5309	N		1					1
5310	N			1			2	3
5311	N			1	1			2
5319	N	1		1			1	3
5320	N		2	2	1		1	6
5321	N				1		1	2
5322	N		1					1
5329	N				2			2
5330	N					1		1
5339	N			1				1
535	N		1			1	1	2
5379	N			2			1	3
5513	N		2					2
5602	N					1		1
5609	N						1	1
5621	N		1	1	1		1	4
5631	N				1	1		2
5670	N			1				1
5679	N		2		1			3
5694	N		1	1				2
5699	N	2	4	3	1	2	5	16
5710	N	10	21	26	8	28	18	100
5718	N	4	5	11	5	4	7	35
5719	N	5	17	21	4	21	17	84
5730	N				1		1	2
5739	N	2	5	4	3	3	6	22
5741	N		1					1

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
5761	N			1				1
5769	N	1						1
5770	N	3	2	5		2	2	14
5771	N					1	1	2
580	N		1			2	1	2
581	N	1	1					2
582	N	1	1	3	5	4	3	17
583	N			1				1
5900	N			1				1
592	N						1	1
5931	N			1				1
5932	N	1	3	4	1	1	1	11
5933	N				1			1
595	N			1				1
5990	N	1						1
6075	N			1				1
6821	N		1					1
6951	N			1				1
7131	N			1				1
7160	N					1		1
7179	N		1					1
7201	N			1				1
7202	N			1				1
7251	N				1			1
732	N	1						1
7340	N					1		1
7341	N			1				1
7478	N						1	1
7551	N			1		3		4
7817	N		1					1
7824	N		1	2	1		1	5
7865	N					1		1
792	N			1				1
7960	N	1				1	1	3
7963	N	3	6	9	4	5	5	28
7969	N	4	2	4	1	2	4	16
E802	N		1					1
E804	N		1					1
E805	N	1				2		3
E807	N					1		1
E810	N		3	2	2	5	2	14
E812	N	6	12	21	3	40	14	92
E814	N	2	1	7	2	9	9	30
E815	N	7	11	4	4	6	4	35

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
E810	N	6	13	12	5	16	13	65
E818	N			1	1	2		4
E819	N	8	15	26	14	43	28	129
E820	N					1		1
E823	N		1	1	2	1	2	6
E826	N	1				1	1	1
E830	N		3	3		4		10
E832	N	2		2	2	3	2	11
E835	N					1		1
E837	N	1					1	2
E840	N	1		1			1	2
E841	N	12	38	16	5	25	27	114
E842	N		1					1
E843	N						1	1
E844	N	1	1	1				3
E852	N				1			1
E853	N						1	1
E854	N		1					1
E859	N			1		1		2
E860	N			2	2		1	5
E869	N		1	1			1	3
E870	N					1		1
E873	N		2	1		4		7
E874	N		1				1	2
E875	N			2		1		3
E880	N		1	3		4	1	7
E881	N		2				1	3
E882	N					1	3	4
E883	N		1			1	1	3
E884	N	1		1	1	4	5	9
E885	N		1					1
E887	N	2	2	5		4	3	15
E890	N	1	3	4		4	1	13
E891	N	1	1				1	2
E892	N	1				1		2
E894	N		1					1
E898	N		1	1			1	3
E899	N	1		2	1		1	5
E901	N					1		1
E902	N					1		1
E904	N	1		1			1	3
E905	N	1		1				2
E907	N						1	1
E908	N			1				1

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
E910	N	4	6	8	4	7	10	36
E911	N	1	3	2		1	3	10
E912	N			1		2	2	4
E913	N		2	3		2	1	8
E915	N						1	1
E916	N	1	1	2	4	4	1	12
E917	N		2		2	2	1	7
E918	N	1		1		2		4
E920	N		1	1				2
E921	N		1					1
E922	N		1	8	1	4	7	21
E923	N	2		5	1	3	1	11
E925	N	2	2	5		2	3	14
E927	N					1		1
E928	N		3	4		2	3	11
E929	N	4	6	10	4	16	5	44
E930	N	1		1		1		2
E931	N		1	1				2
E936	N	1						1
E940	N		1				1	1
E944	N			1				1
E946	N		2	2			1	5
E947	N		1					1
E950	N	2	3	2	1	4	4	15
E952	N		5	4	4	10	4	26
E953	N	2	4	3	5	4	3	21
E954	N	1	2	1			1	5
E955	N	5	23	31	11	28	28	120
E956	N			1		1		2
E957	N		1			1		2
E958	N			1		2		3
E960	N		1				2	3
E963	N		1			1		2
E965	N	7	15	17	5	12	19	74
E966	N	2	3	10	1		2	17
E968	N	1	2	3	1	5	3	13
E970	N	1		1	1			3
E980	N		1	4	1	2	1	9
E982	N		1	1	1	2	1	6
E983	N					1		1
E984	N			2	1			3
E985	N	3	3	4	2	1	3	15
E988	N		3	1		1	1	6
E991	N	4						4

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

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*The total is less than the sum because some men were present at more than one series.

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(USED IN ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
E993	N	1					1	2
E994	N	2	2				1	5
E995	N	4	8	6	6	3	1	26
TOTAL	N	412	1232	1175	410	1129	966	5113

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE;
CA=CASTLE; RE=REDWING)

NUMBERS OF DEATHS BY CAUSE AND SHOT/SERIES, THROUGH 1982
(INELIGIBLE FOR ANALYSIS)

C.O.D. (I.C.D. 8)		SM	OP	UK	GR	CA	RE	TOTAL* COHORT
UNK	N		8	7	3	3	3	24
0381	N					1		1
1460	N						1	1
149	N		1					1
1541	N						1	1
1621	N	1	4	1	2	1	1	9
1890	N			1				1
1959	N					1		1
1977	N			1				1
1978	N		1					1
1990	N					1		1
201	N				1			1
2022	N					1		1
2040	N		1					1
2041	N	1						1
2509	N					1		1
3959	N					1		1
4100	N			1				1
4109	N		2	1		2	2	6
4121	N		1					1
4122	N					1	1	2
4123	N			1				1
4272	N					1		1
4299	N					1		1
4369	N		1					1
442	N					1		1
485	N		1					1
5193	N			1			1	2
5719	N		1					1
7969	N					1		1
E812	N	1	2		2	1	1	7
E814	N					1		1
E816	N			1		4	3	8
E819	N			2	1	3	9	15
E841	N		5	1				6
E866	N		1					1
E884	N					1		1
E890	N	1						1
E910	N		1			2	1	4
E923	N			1				1
E965	N			1				1
E966	N			1	1			2
E995	N				1			1
TOTAL	N	4	30	21	11	29	24	117

(SM=SMOKY; OP=OTHER PLUMBBOB; UK=UPSHOT-KNOTHOLE; GR=GREENHOUSE; CA=CASTLE; RE=REDWING)

*The total is less than the sum because some men were present at more than one series.

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